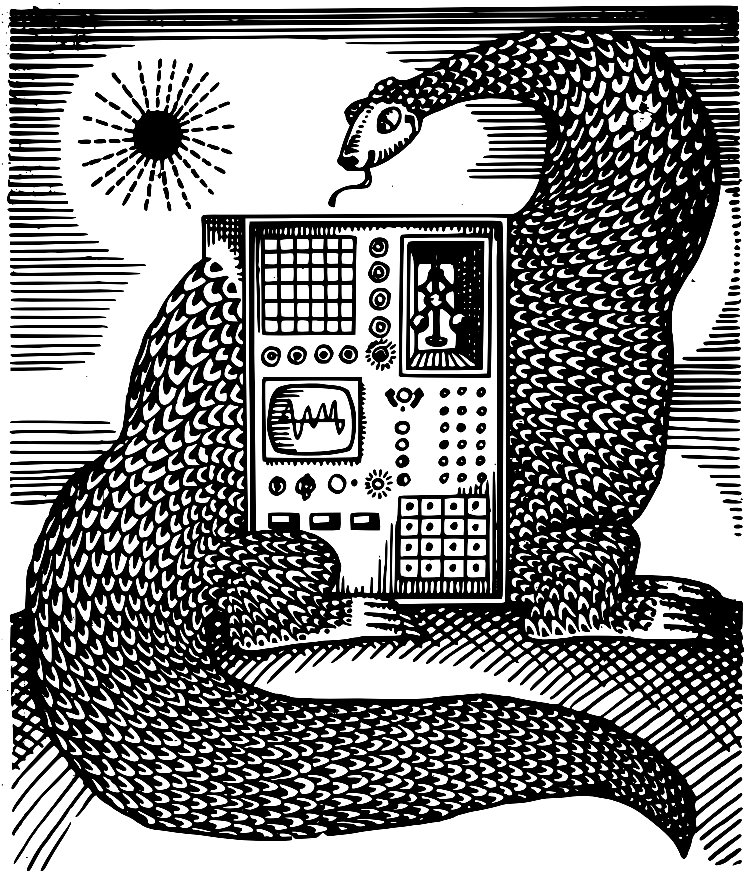
Yelena Saparina



CYBERNETICS WITHIN US

PEACE PUBLISHERS

Е Л Е Н А С А П А Р И Н А

КИБЕРНЕТИКА ВНУТРИ НАС

ИЗДАТЕЛЬСТВО ЦК ВЛКСМ
«МОЛОДАЯ ГВАРДИЯ»

На английском языке

Yelena Šaparina

CYBERNETICS WITHIN US

Translated from the Russian by VLADIMIR TALMY

PEACE PUBLISHERS MOSCOW

UDC 519.95:611.81 =20

Can a rat tell the difference between a Raphael Madonna and a Picasso Girl in Blue? Would a Martian (if there is such a thing) recognize a live cat after having seen a photograph of one? Can a "seeing" electronic machine be made to tell a cat from a dog or an A from a B? How would it go about "computing" the image? And is "machine thinking" anything like human thinking?

These and other such problems are investigated in the branch of cybernetics that studies living systems: bionics, as this ultramodern science is now called. It developed when scientists began to compare the design and operation of electronic systems with living organisms. Our body, they found, is a complex cybernetic system controlled by countless self-regulating devices. In fact, every single cell of our body is an automatic control device in its own right. Millions upon millions of tiny cybernetic units are constantly at work within us. They maintain normal blood pressure, control the composition of the gastric juices, ensure the rhythmic contraction of the heart and lungs, and do a thousand other things that come under the heading of "vital functions" of the organism.

How they work and how our body functions is described in this popular exposition, which requires no previous knowledge of cybernetics, biology, electronics, or any other subject for that matter (except reading, of course).

AUTHOR'S PREFACE

Cybernetics is said to have emerged at the confluence of at least five sciences: automatic control, mathematics, logic, biology, and communication theory. This may be the reason why to this day new definitions of cybernetics are still being suggested in an effort to reflect all aspects of this versatile science. Academician Berg once joked that he knew at least two score such definitions, and that he had probably not yet heard the last of it.

In preparing this book I interviewed many scientists, young and old, and each had his or her own ideas on the scope and content of cybernetics. There were those who would discuss their work for hours on end and those who preferred to escape to their laboratories with a perfunctory apology, enthusiasts of the new science and wary sceptics, different people with opposing views and ideas about the same problems.

It is this diversity of opinions and approaches that makes it very hard for the uninitiated to get a clear understanding of cybernetics. At last you seem to have understood a problem, then you arrive at another laboratory and find with dismay that the workers there tackle the selfsame problem from an entirely different aspect. And it's no use trying to determine who is right; the science is still young and therefore controversial. Furthermore, many people draw a line between engineering cybernetics and biological cybernetics.

The latter, the cybernetics "within" us, can be said to have been born twice. Millions of years ago nature built into living organisms a perfect automatic system with a remarkable control unit—the brain—joined by nerves to all parts of the body. Then the time came when the human brain invented self-regulating systems, without suspecting that it had actually produced a remote analogue of the wonderful control mechanisms inside the living body. Only after cybernetic machines became a fact did it occur to physiologists that living organisms might be controlled by something like these devices.

Thus cybernetics, which developed from a comparative study of machines and living organisms, returned to biology, remaining at the same time in the engineering domain. In short, as someone once remarked, cybernetics is a science in which the physiologists tell engineers how to build machines, and engineers tell physiologists how life works. Whenever people discuss cybernetics they inevitably arrive at the crucial question: Will machines ever get so "clever" as to learn to "think"?

I, too, could not evade that question, although, as you will see, I put off answering it to the very end. In fact, I didn't answer it at all: I have given the facts and leave the answer to you.

I have undertaken to be your guide in a rather unusual journey through books, research institutes, laboratories and lectures. You may find some things amusing and some doubtful. My only hope is that you will not find them boring. And finally, I am a juornalist not a scientist. This, however, might not be so bad: at least you will be seeing things through the eyes of a layman.

BY WAY OF AN INTRODUCTION

The past decade or so has seen the rapid advance of cybernetics, a new science concerned with the study of control and communication.

The science of control covers three main spheres: control of machine systems and manufacturing processes; control of organized human activity, such as finance, insurance, commerce or transport; and control of processes in living organisms. To the latter belong the physiological, biochemical and biophysical processes associated with the vital functions of the organism whose purpose is to ensure its survival in an overchanging environment.

Modern instruments and means of gathering, storing and processing information about the intricate structure and functioning of living organisms have opened up remarkable vistas to biology. The close co-operation of electronics experts, mathematicians and biologists is yielding important theoretical and practical results of increasing value.

Scientists are penetrating deeper and deeper into the most complex laws of living nature. Electronic diagnosing machines are coming into use in the medical profession. Devices have been built that can substitute for the heart, lungs or

kidneys during an operation, thus greatly facilitating the work of surgeons. Broad prospects are opening up in the study of higher nervous activity.

The approach to the study of physiological phenomena in which the various systems of the organism and the factors affecting it are artificially separated and examined individually cannot be used to investigate the laws governing the functioning of the organism as a whole. The properties of individual nerve cells could be, and have been, studied in great detail. It is impossible, however, to derive directly from the properties of individual cells such complex aspects of cerebral activity as thinking and speech.

For the physiologist the attraction of cybernetics consists in that it deals with complex systems, physiological systems included, and the laws governing their operation.

When designing electronic machines, man learns from nature, just as he learned from her in developing his first simple tools, which were "extensions" of his limbs. The brain, of course, is immeasurably more complex than arms or legs, and in many respects it is the as yet unattainable ideal of the engineer. In spite of its compactness, light weight and negligible power consumption, it is an extremely reliable system with a substantial safety margin.

On the other hand, the brain is rather slow, its memory is not too good, it often forgets important things, and it succumbs to fatigue and malnutrition. The brain is an extremely delicate piece of machinery that must be carefully protected from jars and jolts. It also undergoes pathological changes due to disease and ageing.

In endowing electronic machines with some of the brain's simpler functions the engineer seeks to make good some of its shortcomings. The greatest gain in this respect has been in speed. Machines, however, are far inferior to the brain in reliability, and maintenance is a serious problem in itself.

The question naturally arises whether it is possible to simulate the brain electronically, at least in part. One of the newest branches of cybernetics is called bionics, which deals with the development of electronic neuron analogues and their utilization in computing machines. The prospects of this new scientific discipline are exciting indeed.

The development of "learning" machines, which not only carry out the programmes built into them by their designers but also accumulate and utilize the results of subsequent experiences, has opened up a vista of remarkable possibilities. Work is at present being carried out on machines capable of interpreting speech, writing and visual images directly, and even of formulating concepts.

An increasingly important place among the cybernetic disciplines is occupied by "mathematical linguistics", a new branch in the science of language which is closely linked with the development of "machine" languages and the automation of translation from one language into another and the abstracting of scientific literature.

With cybernetics steadily invading all spheres of life, a popular exposition of its applications to medicine, physiology, psychology and lin-

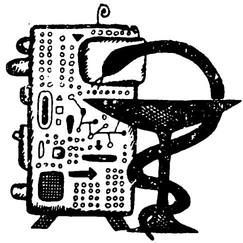
guistics is certainly welcome. Yelena Saparina has successfully coped with the difficult task of presenting complex problems in a simple and entertaining manner, and the reader will undoubtedly find much of interest in her book.

Alexander Berg,
Academy of Sciences of the U. S. S. R.

CONTENTS

IV. IF MACHINES WENT TO SCHOOL

V. PERCEPTION IN MACHINES



I. DISEASES OF MEN AND "DISEASES" OF MACHINES

Cybernetics and the Heart

Professor Nikolai Amosov, head of the Kiev Institute of Thoracic Surgery, was one of the first medical doctors to realize the need for surgeons to be good engineers as well.

"Cybernetic machines are essential in our work," he told me when I came to interview him at his institute in Kiev. "We have built several machines which we use in operations on the heart, lungs, and other organs."

Professor Amosov seemed quite at home with engineering terms, and I thought that he could hardly have discussed mechanical hardware with such ease if he were only a doctor.

"As a matter of fact," he told me, "at first I wanted to be an engineer and I joined the power engineering department of a polytechnical institute. But medicine also appealed to me, so I entered a medical college as well."

He was an inquisitive student and spent many days and nights over his books. As an engineering

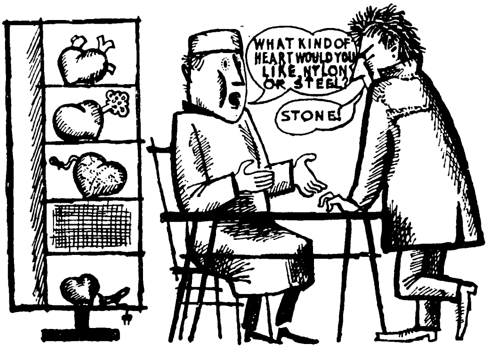
student he constructed boilers of unusual design. As a medical student he investigated the workings of the human heart. For a long time it was a tug of war between the two professions. He graduated from the medical college with honours and was recommended for a post-graduate course. At the polytechnic Dr. Amosov designed an original aircraft with a steam-turbine engine. He received his engineering diploma (also with honours)—and took up medical practice in the country. The fight between engineer and doctor might have continued much longer if not for the war. He became—and stayed—a surgeon. For in surgical practice the doctor and the engineer finally came together. Amosov the surgeon began taxing Amosov the engineer for new solutions to medical problems.

From a modest start of ten operations in one year Amosov rapidly gained in skill, and soon he was making hundreds. In seven years' time he topped the thousand mark.

"One Thousand Lung Operations" was the title of Amosov's paper in a surgical journal in which he gave a detailed account of difficult operations and his search for new surgical solutions. His conclusion was that of an engineer: the only hope for advance in chest surgery lay in the construction of new machines and apparatus.

Amosov devoted many evenings to designing medical hardware. Soon his ideas took on concrete form. When a surgeons' conference was held in Kiev, Amosov arrived with a brief paper and a huge trunk. He hauled the trunk on to the dais and unpacked an artificial lung designed to take over a patient's breathing during operations.

That was in 1951, and Amosov remained in



Kiev to head the Thoracic Surgery Clinic. Thoracic surgery deals with operations on the lungs and heart. Ten years later Professor Amosov had three thousand lung and four hundred heart operations to his credit.

He performed his first heart operation at a time when congenital defects were removed by means of the simplest instrument: the surgeon's finger. That was many years ago. Then engineers devised an instrument to replace the finger. It was used to snip out bits of the cardiac muscle blocking the flow of blood between the ventricles and auricles or to the blood vessels leading out of the heart. Amosov tried out many instruments of various design before he got down to building his own. The one he made was simpler, more convenient and, most important, absolutely reliable, precluding any possibility of accidental injury. But it could rectify only minor defects.

Amosov delved deeper and deeper into the secrets of the heart with the aim of finding cures for its gravest ailments. Soon he was performing such major "repair jobs" as sewing up holes or

mending them with plastic patches if they were too big, fixing up cardiac valves and replacing whole sections of arteries.

With the complexity of operations increasing, however, it became more difficult to keep within the limited time during which one could operate on the living, beating heart.

"How much easier it would be to operate on the heart if I could only stop it for a while," the surgeon thought.

"Well, introduce a mechanical pump, switch off the heart and operate on it dry," the engineer replied.

An artificial heart was the answer, and in 1957 the first heart machine went to work in the operating room. But how different it was from the compact, tireless "machine" we carry under our ribs! The human heart weighs ten ounces or so. The artificial heart was contained in a box waist high and it took two men to move it. The engineer in Amosov revolted against the sight. An artificial heart had to be simple, portable and, furthermore, more reliable.

Again the doctor spent nights at his drawing board and carried out calculations and experiments. The new artificial heart was much smaller than all its rivals and required only a pint of blood to start it working. Since then Professor Amosov's machine has helped to save scores of lives.

"Oh, no," Amosov hastened to add, "it is not at all completed. One could say that it is in a continuous process of perfection, with new devices and gadgets being continually added to it."

The first addition to the artificial heart was a lung unit. The vessels along which the blood

flows from the lungs to the heart lie very deep and are hard to reach. This makes it virtually impossible to stop the heart without stopping the lungs, and oxygen must be supplied to the blood by artificial means. This requires a special surgeon's assistant during operations to look after the oxygen content of the blood.

"The best thing, we decided, would be for the machine to do the job itself," Amosov went on, his eyes sparkling with enthusiasm. "Our goal is to make it completely self-contained, keeping blood pressure at just the right level, controlling the oxygen supply as required by the patient's organism, and so on. It must operate automatically on a completely self-regulatory basis. There's cybernetics for you."

My acquaintance with cybernetics had begun with one of its less known applications—the control of "auxiliary" surgical equipment. Later I was shown sundry designs and blueprints of artificial lungs, automatic anesthetic units and other devices whose operation is controlled by the organism: they are run by commands from the lungs, heart or brain of the patient, which induce the required operating regime and then maintain it.

On the other hand, there are many cases when it is the apparatus itself that controls the body when an organ goes out of order. In such cases the commands come from outside and, for example, they make the heart beat rhythmically. An application of cybernetics to medicine is seen in the construction of prosthetic appliances to replace internal organs and limbs.

Electronic Doctor

Doctors say that the best thing for the successful treatment of a disease is its early detection. A correct diagnosis is better than the most sophisticated machine in the operating room. The future of medicine, they say, lies in diagnosing machines.

Frankly speaking, at first I couldn't understand why doctors seemed so keen on electronic diagnosis. After all, I thought, the very best automaton would never be able to provide the human attention and solicitude of a doctor.

"What do we need 'electronic doctors' for?" Professor Amosov repeated my question. "Well, it often happens that an operation on a patient fails to confirm the original diagnosis of the disease. A doctor is only human and he may have forgotten about a disease or its symptoms, or he may have overlooked or misinterpreted them."

This was illustrated by the eminent French cybernetician Francois Paycha, who staged a competition between a machine and a man. He fed 800 symptoms of various diseases of the cornea into an electronic computer together with detailed information about the condition of the patient.

The diagnoses offered by the machine and the doctor were essentially the same, but the machine had listed four more diseases, all of them of a rare kind.

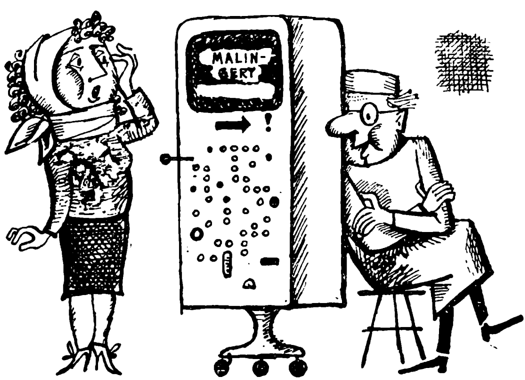
"How could I have forgotten them!" the dismayed doctor exclaimed. "I should have thought of them!"

The reason for his forgetfulness lies in the very nature of human memory: it tends to forget things that are not repeated. Even if the information is

there, whether it will be remembered at the right time or not can depend on many external factors. If a person is tired or worried his memory may well let him down. A machine is unemotional and tireless, its diagnosis is wholly unbiased. Small wonder that doctors are interested in diagnosing machines.

But if anyone imagines that machine diagnosis is such a simple thing he is greatly mistaken. The symptoms of a disease are numerous. There are primary and secondary symptoms, they combine in many ways, and every disease has a number of variants. A man displays a high degree of flexibility in comparing and evaluating the symptoms of a disease and he determines its characteristic features from a vast array of facts. Modern computers are unable to do this.

A tremendous amount of information can be fed into a computer, much more than a human brain can cope with. The difficulty lies in linking up the various data. To remember one link between two facts is just as difficult, as far as the machine is concerned, as remembering the fact itself.



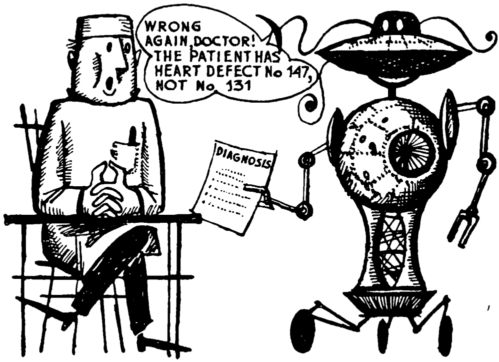
And it takes up just as much space in the machine's "memory". This is one of the limitations of machines stores.

Computers operate at high speeds, of course, but it is often forgotten that only those calculations utilizing the machine's relatively small "computing store" are said to be instantaneous. It takes much more time to extract information from the "permanent store", and as often as not it may take the computer longer to solve some problems which are relatively easy from the human standpoint.

The Soviet *Ural-1* computer, for instance, can take as much as two and a half hours to diagnose a disease. True, it is not a very fast machine, especially in comparison with the Kiev computer, which takes only two minutes. But this performance is achieved only after the doctor has already done three-quarters of the job: tabulated the symptoms of various diseases according to importance and relevance, and compiled and translated into machine language a programme of operations based on the logical thinking of a doctor making a diagnosis.

This is a substantial part of the work, and the most laborious at that. Take tables of symptoms, for example. By variously combining only 90 symptoms of heart diseases Professor Amosov was able to compile a list of 156 different heart ailments.

The patient's symptoms are fed into the machine, which compares them with the 156 sets of symptoms built into its store. After sifting and weighing the relevant information it chooses five diseases which correspond closest to the symptoms. The machine thus makes five diagnoses, indicating the relative trustworthiness of each.



It is left to the doctor to asses the results and choose the most correct diagnosis.

The doctor's contribution is substantial, and it is not only functional but creative as well, demanding thought. His is the decisive word.

"Which means," I remarked with some relief, "that even a 'thinking' diagnosing machine can't replace a doctor."

"Of course not," Professor Amosov smiled. "Why should it? But it will make the doctor more efficient. Once we decided to test our diagnosing machine. We fed twenty-five records of old medical cases from our clinic into it to see just how well it worked. Its diagnoses coincided with those of our clinicists. But when we took case histories from another clinic, the machine's diagnoses did not coincide with those of the doctors. That is to say, the views of the machine and the attending physicians differed.

"The reason, we found, was that our methods of examining patients differed. Doctors go about gathering the essential data about their patients in various ways. So we thought that the best

thing would be for the machine to get the necessary information not from the attending physician but straight from instruments. We would thus be able to eliminate the subjective human evaluations of the doctor. This is what we are currently working on. Programming the machine and storing the necessary data is only half the job. We now want to connect it directly to the measuring instruments and teach it to analyse their readings. Then we shall be quite sure that a diagnosis is accurate. We shan't be having as many opinions as there are doctors, as is often the case today. We shall no longer have to accuse doctors of a subjective approach. There will be no going against the water-tight logic of the machine."

The Equations of Health

"Machines doing the work of laboratory assistants, measuring blood pressure, taking x-ray pictures and electrocardiograms? No, that is not my idea of the road along which medical cybernetics should develop." Professor Mikhail Bykhovsky, head of the cybernetics laboratory of the Vishnevsky Institute of Surgery, paused. "Our idea is to improve the diagnosing process itself, to make machines determine diseases better than the best doctors. In a nutshell, we want a diagnosing machine that 'thinks' mathematically; instead of scanning a set of symptoms and picking the relevant ones on a simple 'yes' or 'no' basis it should *compute* the disease."

One of the main units in Professor Bykhovsky's laboratory is a *Ural-2* computer, which he uses to compute diseases according to mathematical

formulas. The laboratory is appropriately staffed with physicians and mathematicians, and although it belongs to the Surgical Institute and its purpose—automation of the diagnosis of heart diseases—is purely medical, the mathematicians are the men who count most, and in more than one way.

In Kiev the problem is tackled from the medical aspect: the cyberneticians tailor their solutions to the doctors' requirements. In Moscow they take a mathematical approach, the idea being not merely to translate a physician's reasoning into mathematical formalism, but to develop new, mathematical methods of diagnosis.

The combination of mathematics and medicine produces some strange notions indeed, and terms like "disease variables", "phase portrait of changes in pathological state" or "probability density of representative points of normal and pathological states" do not tend to facilitate the layman's understanding of the essentials. Soon, however, the mathematical terms come to life and develop into a precise, graphic picture of a disease.

You are healthy: your body's temperature is 36.6° centigrade (or 97.9° Farenheit, if you prefer), your pulse is 70 strokes a minute, your blood's hemoglobin content and pressure are normal. Even such a simple description of your state makes quite a mouthful. The data can, however, be recorded concisely, in terms of $x_1=36.6$, $x_2=70$, etc. An even more graphic representation is given by two co-ordinate axes with various points denoting the respective values. If you fall ill the x values change, and the points move to new places in the co-ordinate system. Thus the states of a healthy or ailing organism can be represented diagrammatically.

Several such diagrams for a number of days in succession would show the various points in motion. In mathematical language, we obtain the locus of each individual point, and when all these are considered together we obtain a phase portrait of the disease.

If the body's characteristic points (which describe its state) move from the "healthy domain" of the diagram to the "sick domain", this indicates that a disease is developing. If the characteristic points eventually stop in some definite region this means that the disease has turned chronic. A reversal of this trend would mean that the patient is recovering.

It is thus possible to follow the course of a disease by purely mathematical means. This imposes new requirements on diagnosis. Suppose a doctor examines a patient and finds that his condition is characterized by a point M. The first thing to do is to determine the domain of the diagram, "healthy" or "sick", in which it lies, which is conventionally called reaching a diagnosis. This is only the beginning. The doctor has several of the point's co-ordinates given by the results of clinical tests, medical examinations and the patients answers to questions. This information is not sufficient for him to locate the point exactly. Instead, it gives a certain region in which the point most probably lies. If the region lies within a single pathological domain, the diagnosis is completed. Usually, though, the symptoms of various diseases overlap and as a result the region covers several pathological domains.

One cannot say: "Symptom z is characteristic of disease y." The rule usually is: "Symptom z means that there is a fair chance of the disease

being y." A doctor goes through a process of logical reasoning to decide which of the several possible diseases indicated by the given symptoms his patient is suffering from. The diagnosing machine does this mathematically, by means of exact calculations and, ultimately, by utilizing the formulas of probability theory.

The next step after the disease has been determined is to prescribe a treatment. From the mathematical point of view this means to plot a path for the "characteristic point" which would bring it back to the "healthy domain". There may be several such paths, of course, and it is the machine's duty to choose the best one, that is, prescribe the best treatment. This, too, is done with the help of mathematics.

Machine diagnosis, we find, has come to mean much more than determining a disease. After prescribing a treatment the machine could be made to check the organism's response and introduce any necessary changes. The diagnosing machine could develop, in fact, into a "sickness control" machine.

"This is all very well," Professor Bykhovsky remarked. As a mathematician, a representative of the exact sciences, Bykhovsky is, in his own words, a down-to-earth man accustomed to thinking in terms of feasible things. "But we'll leave the treatment of patients to the doctors. Our concern lies in diagnosing, and our task is to make machines diagnose diseases mathematically."

"Can't a man do the same thing: take the formulas, plot the curves and compute the disease like the machine does?" I asked.

"For one thing," Professor Bykhovsky replied, "before doctors could undertake such computations they would have to be taught higher mathematics. Secondly, even if such versatile experts were trained, they could never match the machine, which calculates at the rate of five thousand mathematical operations per second. Let the electronic doctors do the diagnosing. Besides, we have other jobs for them, such as analysing and summarizing the work of clinics and hospitals."

Thousands upon thousands of case histories, which take up so much of a doctor's time, are gathering dust in medical archives. They contain countless valuable observations which could be of great help to young doctors. The knowledge and experience of every doctor remains practically his own. Machines can be put to work storing and analysing such information. They can thus contribute both to medical practice and to medical theory.

A step in this direction was made when workers of the cybernetics laboratory added an "experience unit" to the computer's memory (storage) and logic units. They fed 700 case histories into the

machine as a basis for its theoretical analysis programme. The initial experiments were successful, and the machine's correct responses increased to 80-90 per cent.

Diagnosing machines will find many other spheres of application in which they will be much more competent than human doctors. One such application is the analysis of electrocardiograms. You have probably seen the jagged trace of this electrical record of the heart's activity. By looking at it a doctor may be able to judge the heart's ailment. For example, he can tell that the left ventricle is dilated. An experienced physician may be able to detect smaller defects, but no one can see more than is recorded on the strip. Yet a machine can.

When a machine is made to analyse an electrocardiogram it resolves the curve into simple components in which it can detect changes which are smeared out when the components are joined together. In this way doctors, American specialists in cardiovascular diseases, detected a heart ailment before the patient himself had felt anything wrong.

Detecting diseases before they appear, forecasting sickness before it develops. This is something to make you sit up!

My visits to two laboratories working on diagnosing machines brought me into contact with representatives of two schools of biological cybernetics.

In one the promise of new, breath-taking vistas acted like a powerful stimulant. It gave men wings and went slightly to the head. Ideas got bolder and projects rushed out, the one more fantastic than the other. They may be unrealizable today—in their dreams these scholars are

far ahead of our time and opportunities. In such a laboratory one can be sure to find a pet fantastic project, something like a manmade nylon electronic heart.

Others view cybernetics as just another very convenient tool wrested from nature for research purposes. Such people don't like to discuss their plans, they flatly refuse to engage in forecasting the future and they dislike the newsmen's thirst for "planned sensations". They are reluctant to discuss their plans, and try to get away with a few remarks. Yet if you dig down beneath the superficial prosiness you find a wealth of fantastic ideas.

The nature of cybernetics is such that whatever path you take you are bound to arrive at wonderful discoveries and remarkable juxtapositions. For what can be more remarkable than the juxtaposition of "thinking" machines and the human brain that has created them!

Some machines, for instance, suffer from the same ailments as you and I. Can you imagine that?

Feedback and Physiology

Many biologists were highly indignant when Norbert Wiener first compared feedback control in men and machines. "If my old car squeaks and groans like a rheumatic when I drive it," the Frenchman Paul Cossa remarked, "can I say that it has rheumatism? Or if the carburettor wheezes when I step on the gas, can I say that it has asthma?"

Paul Cossa, however, was comparing noncomparable things and the absurdity of the result is hardly surprising. But what if we compare the

basic, fundamental aspects of machine operation and body functions—the systems of control? For the body's control system—the nervous system—can be compared with mechanical control systems such as automatic regulators and governors.

If one carries out a process of abstraction and enquires what these various control systems have in common, one finds that their operation can be described by precisely the same mathematical formulas. These formulas can be used to describe the operation of a steam engine, an automatic steering device or the nervous system.

In Moscow there is a neurosurgical clinic where patients are received by doctors and mathematicians. I, too, went there, though fortunately not as a patient. Even so, the idea of a mathematician receiving sick people seemed rather strange. I wondered if his questions to his patients were technically worded, something like, 'Well, and how are your characteristic parameters today?' instead of the ordinary 'What's your temperature?' But then, I thought, a doctor-cum-mathematician is hardly a stranger creature than an electronic doctor.

I knocked on the door of the physician's office, wondering whether the interview would be more of a medical or a mathematical nature. I pushed the door open and saw an ordinary doctor with his inevitable stethoscope and little hammer for checking knee reflexes. I wondered who took care of the mathematical side.

"Oh, no," the doctor responded to my inquiry. "I'm not a mathematician. He's gone to fetch the next patient. We examine them together. Or rather, I do the actual examining and he translates the results into mathematical formalism."

A patient came into the room. While he sat at rest in his chair there seemed nothing wrong with him. However, when the doctor offered him a cigarette, he swung his hand past in trying to take it. This was followed by an equally futile swing in the other direction. His hand swung back and forth and he was unable to take the cigarette. The doctor offered him a glass of water. He could not carry it to his mouth and emptied it in these swings.

"Intention tremor," the doctor wrote in the case history.

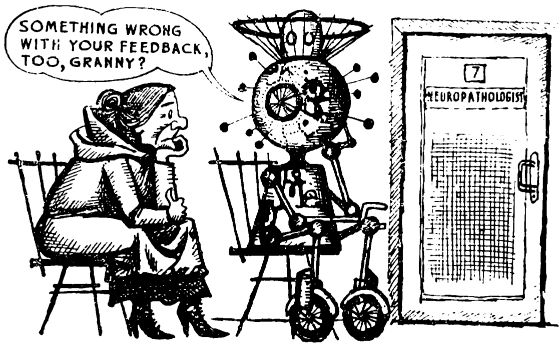
"Reverberation," wrote the mathematician. "It's the same thing," they told me. "One is the medical and the other the mathematical diagnosis. Both denote a disorder in the sections of the nervous system responsible for co-ordinating body movement."

Another patient came in. It was immediately evident that there was something wrong with him. He walked with a peculiar uncertain gait, starting each step with a kick and throwing each leg in front of him more than was necessary for a normal step. The doctor asked him to touch the tip of his nose with his finger. His hand swung wide of the mark.

"Hypermetria," wrote the doctor, and the mathematician jotted down a formula in his notes.

"Another case of a fault in the motor control system," he commented for my benefit.

The next patient also walked with an unsteady gait, though it was somewhat different from that of the previous one. The doctor asked him to write a few words on a slip of paper. The letters jumbled together in an erratic scrawl. The man could control his hands no better than his feet.



"Shut your eyes," the doctor said. He walked up to the patient and lifted the man's arm. "In what position is your right arm?"

The man shrugged his shoulders with a puzzled air.

"Open your eyes," the doctor ordered. "Now look at your arm, shut your eyes and keep your arm outstretched until I tell you to lower it." The doctor indicated with his eyes that I should observe the patient. In a minute or two his arm slowly dropped.

"In what position is your right arm now?" the doctor asked again.

"Outstretched," the patient answered.

"A fault in the paths which transmit sensory information," the doctor remarked." *Tabes dorsalis* in medical nomenclature."

"This," I thought, "is probably how the mathematician Norbert Wiener studied various disorders of the nervous system." I knew that he had spent several months working at the neuropathological clinic of the well-known physiologist Arturo Rosenblueth. He attended medical

examinations of Dr. Rosenblueth's patients, and the realization steadily grew upon him that many symptoms of nervous diseases bear a remarkable similarity to symptoms of faults in automatic mechanisms.

Take, for example, the automatic steering mechanism of a ship. If something goes wrong with it its response fails to correspond to the input signals. It turns the rudder too much and the ship swings off course. The action is duly registered on the tiller, and the mechanism turns the rudder back, but again it overshoots. As a result the ship yaws on its course instead of steering a straight line. Something like the patient swinging his hand in an effort to pick up a cigarette or touch his nose, isn't it?

In the case of the automatic steering mechanism the fault very probably lies in the telltale mechanism informing the control unit of the extent to which the order has been carried out. This mechanism is known as *feedback*. When the control system lacks correct information concerning the performance of the effector units it is unable to ensure a correct response to its commands.

The analogy can obviously be extended to human "machines" (patients) whose "rudders" (arms or legs) cease to obey orders from the control unit because of faults in the feedback conducting paths (nerves).

Thus men and machines may suffer from the same kind of ailments. Doctors are coming to recognize this, and from recognition it is but a short step to the practical application of this remarkable analogy. It is so much easier to pinpoint a defect in a machine than in a living organism. An engineer can even dismantle a machine. Mechanical analogies of nervous disorders

will help doctors to establish the nature of defects inside the human body. And the idea is not to restrict these applications to diagnosis alone. Some doctors are already dreaming of the time when such "cybernetic" diseases will be cured in ways analogous to the methods of repairing mechanical control systems.

Any automatic control system, they say, is provided with knobs and switches for tuning and adjusting. Similar "knobs" are available for our bodies, and in much greater number than can be provided on the best of machines. These are all kinds of medicines and electrical and electronic apparatus such as high-frequency generators, quartz lamps and stimulators or pace-maker units. The doctor uses these tools to act upon a patient's organism and control its behaviour—in other words, to adjust and tune the regulating mechanism of internal processes. Today he must frequently "regulate" by rule of thumb and intuition. Why not make a machine compute the requisite amount of "tuning" and "adjustment" for each particular case?

Many diseases, like hypertension, gastric ulcer or goiter, which are not so obviously due to faults in the body's control mechanism (the nervous system) are now being reconsidered from the "cybernetic" point of view.

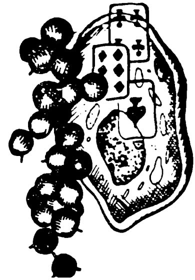
It was long considered, for example, that hypertension was a result of kidney malfunctioning, and it was accordingly treated with drugs acting on the kidneys. Functional disorders of the thyroid gland were treated by introducing thyroid extracts into the blood stream.

Apparent improvements are usually observed in such cases, but for the patient to continue to feel well he must take larger and larger doses of

the drug. This is because the cause of the disease remains unaffected. These disorders are now attributed to a malfunctioning of an automatic system, known as *homeostasis*, which controls the vital functions of the organism.

In the old method of treatment the doctors usually acted only on one of the secondary loops in the body's complex homeostatic system. In order to achieve the required results it is necessary to act directly on the main control system.

The problem thus consists not in a cybernetic approach to diagnosis, nor even in a cybernetic approach to disease. It consists in a cybernetic approach to the human body as such: the cybernetics within us. Let us have a look inside ourselves and see how the cybernetics of living organisms operates.



II. ONE HUNDRED MILLION MILLION AUTOMATIC UNITS WITHIN US

Spades, Clubs, Diamonds, Hearts

"At first, I thought I was seeing things, for both crabs were busy working.

"But there was no mistake. With their thin front pincers they touched bars of metal, producing an electric arc which they used to cut off pieces of metal. With a quick movement they stuffed the pieces into their big mouths. Something buzzed inside them and showers of sparks flew hissing out of their jaws. With their second pair of legs the mechanical creatures fished finished parts out of their mouths.

"They assembled the parts according to a definite pattern, on flat platforms which moved slowly out from under each crab. On one platform there was an almost complete replica of the two crabs. An outline of the mechanism could be seen on the other platform.

"Why, these creatures are actually reproducing themselves!"

I recalled this episode from Anatoly Dneprov's sci-fic novel, *The Invasion of the Crabs*, when I first heard that a "self-reproducing" machine had been built at the Institute of Cytology. Dneprov's book is a parody on the time-worn theme of machines coming to life and turning against their creators. In his case they were crab-like machines which began by reproducing exact replicas of themselves, fantastic half-beasts, half-machines which devoured one another and gradually evolved into more powerful and more voracious machines. Finally they developed into horrible monsters, giant crabs, the hardiest and best adapted in the ruthless struggle for survival.

Today one can actually observe "living machines" in action. Not just machines which calculate the design of simpler gadgets, but actual reproducing machines, whose "offspring" are replicas of their "parents".

In living nature reproduction takes place by means of cellular fission. A cell splits into two, the daughter cells divide again, and so on. With each division the number of cells doubles, the various organs gradually take shape, and then the new organism appears. Every such process starts with a single cell, the bearer of a new life. "Written" into it are the instructions which guide nature in building up the specific organism.

Every spring buds burst forth on the trees, new green shoots appear and develop into leaves and flowers. With wonderful consistency nature snips out the petals of pansies, asters or daisies into their fanciful shapes and ties rosebuds into tight knots. Autumn comes and fruits ripen in place of the flowers. Inside each fruit there lies a tiny cell carrying a new detailed programme of life. Spring comes, the sun grows warmer, and the

seed sprouts to turn again into delicate bluebells, the spear-like awns of ears of wheat or the strong tubular stalks of maize—inimitable, intricate living structures which stubbornly repeat themselves from generation to generation.

How does nature cram so much information into a microscopic cell, how does it code the programme for constructing the intricate adult organism? Today a schoolboy knows that nature stores the requisite information in the form of a detailed code which is handed down the generations. Terms like "genetic codes", "hereditary genetic information" and "the cybernetics of living systems" are common parlance nowadays. Yet only a few years ago scientists were still racking their brains in vain to solve the greatest mystery of living nature.

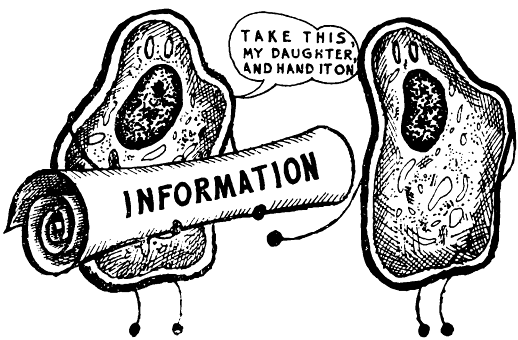
Then the idea was cautiously voiced that our bodies and the cells comprising them are in effect cybernetic systems in which, additionally, there are stored away codes carrying detailed information about the future organism and its development. This was a sensation which spread beyond the limits of biology. Small wonder that crowds flocked to Moscow University to hear physicist Igor Tamm lecture on the genetic code. Scientists rubbed shoulders in the hall with students. Biologists tripping over the unfamiliar mathematical nomenclature argued with physicists anxious to translate the complex problems of biology into the language of cybernetics.

The new theory had its adherents and opponents, and heated arguments frequently flared up at the lectures. They overspilled into the corridors, invaded other auditoriums and swept out to the university campus and into the city streets, where they continued till midnight.

Cybernetics within us, within each tiny cell of our body—

A cell can be regarded as a factory in which the nucleus is the "executive branch", which issues the orders concerning "production". The information needed for the factory to operate—blueprints, templates, production plans—is stored away in coiled strands of molecules. The production shops with the machinery and workers responsible for output are situated in the cytoplasm, the fluid filling the cell.

The hereditary information is stored away in long molecular chains made up of thousands of simpler molecules. Nature has provided four basic "building blocks" out of which the great variety of genetic molecular chains are erected. The American physicist George Gamow used the names of spades, clubs, diamonds and hearts, the four card suits, to denote the four types of "building blocks". Every hereditary molecule can be represented as a sequence of thousands of cards. The order of the suits in the sequence carries the instructions for the germ cell and its



progeny to develop into a rose-bush, a squirrel, or a human being.

In our molecular card pack the number of spades is equal to the number of clubs, and there are as many diamonds as there are hearts. Furthermore, the two red suits join only between themselves, and the two black suits between themselves.

The hereditary "conducting paths" of living organisms possess tremendous traffic carrying capacity and remarkable transmission accuracy. This is hardly surprising, for they must carry information not only concerning the type of life that will develop from the germ cell but also concerning the smallest details of its body structure, including all the individual features of the specific rose-bush, squirrel or human being.

However finely the information may be recorded, however perfect the code in which it is stored, it is nevertheless hard to imagine how it all fits inside a single cell. Still, nature has coped with the problem. The storage capacity of the molecular chain is tremendous.

Such a molecule is like a rope ladder with double rungs, each of which is made up of a pair of "cards". The configuration and sequence of the rungs determine the type of information stored.

When a cell is ready to divide, its numerous "rope ladders" split lengthwise into two, each strand bristling with rung halves. The hearts, for example, are thus separated from the diamonds, and they choose new partners for themselves from the cytoplasm. The total number of ladders is thereby doubled, the cell divides, and each new factory has obtained its own "blueprints" and "templates" and can start producing.

Protein Alphabet

The cellular chemical "factories" engage mainly in the production of proteins. Different cells produce different kinds of proteins, and a cow, for instance, will never produce sheep's hemoglobin in its blood.

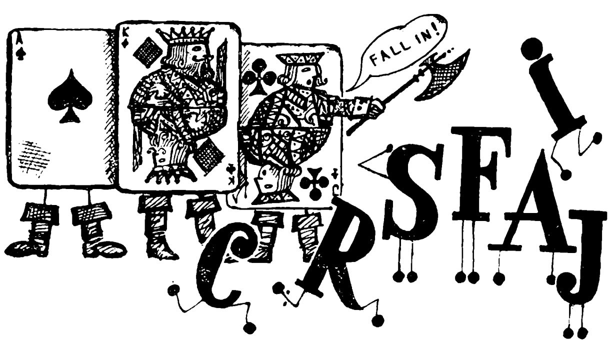
Protein molecules are even longer than genetic molecular chains and it is impossible to enumerate all the different types. But they, too, are nevertheless made up of a limited number of "building blocks", twenty in all. They have been assigned letters, which make up a simplified twenty-letter alphabet. The fundamental "coding problem" is how the sequence of four "suits" determines the sequence of the twenty "letters" of the protein "alphabet".

"Suppose," Gamow writes, "we play a 'simplified poker game' in which each player gets only three cards, and all cards are only the aces of the four different suits. How many different hands can a player have? First of all he can get four different 'flushes': 3 hearts, 3 diamonds, 3 spades, or 3 clubs. Then he can have 'pairs' such as 2 hearts and 1 spade, or 2 spades and 1 club. There are altogether 12 different combinations of that kind, since the suit of the pair can be selected out of four possibilities, while the extra card can be chosen only from the three remaining ones. The lowest hand is a 'bust' with all three cards different, and there are 4 different possibilities in this case (no hearts, no diamonds, etc.). Thus our hypothetical poker player may have any one of 20 different triplets of cards, which is exactly equal to the number of different component parts forming a protein molecule."

Some people might not like the idea of man being nothing better than the result of a poker game played by nature. But the comparison is a happy one, insofar as the choice of this or that letter of the protein alphabet does appear to be determined by a triplet of rungs in the molecular ladder. The number of rungs in a protein is usually an integer of three, and protein "sentences" can accordingly be written down in "three-letter words".

This hypothesis could be checked by matching all possible combinations of the twenty "letters" to triplets of the four "cards". Unfortunately, Gamow writes, this would take much too much time: five thousand million years at the rate of one check per second. An electronic computer capable of scanning a million variants a second would be faster, but it would also not be of much help: working 24 hours a day since the beginnings of the Roman Empire, it would still be a long way from the end of its task.

The scientists decided to attack the protein code in the same way as one would any cryptogram. The first thing is to get to understand some



parts of the message. One of the ways of deciphering a coded message is to determine the frequency of different letters and the combinations in which they occur. The letters of a language obey certain rules of occurrence and association, which makes it possible to decipher a code if the language it is written in is known. Applied to protein "messages", however, this method failed.

One reason was that the available "messages" were too fragmentary as the structure of too few proteins was known and it was difficult to observe any general tendency in the sequence of "letters".

Nevertheless the scientists succeeded in cracking the genetic code. In December 1961, the Spanish biochemist Severo Ochoa reported that he had deciphered four "letters" of the protein "alphabet", and while his paper was going to press he deciphered seven more "letters". At the same time Francis Crick, an Englishman, was also busy. By the beginning of February 1962, the codes for all twenty building blocks from which the different protein molecules are made were known. This was a major scientific achievement.

The code with which the four "cards" controlled the building up of molecule "words" out of the twenty "letters" of the protein "alphabet" proved to be based on triplets. Gamow was right in the main thing. Three "cards" are responsible for the inclusion or noninclusion of this or that "letter" in a protein "word".

This was proved by adding different numbers of "cards" to the molecular "pack" controlling protein synthesis. If one or two new "cards" were included in a molecule it lost its controlling

ability and the code broke down. Only the addition of three "cards" out of four possible suits did not change its properties. The number of "rungs" remained a multiple of three and the protein was essentially normal, though not necessarily of the kind initially contemplated by nature. The next step was to correlate various "card" triplets to the different "letters".

An artificial "card pack" was built as a "cybernetic molecule" consisting of repetitions of one and the same "card". This molecule was made to compose a "word" according to its ability. The resultant protein, naturally enough, was "lopsided", consisting as it did not of twenty different letters but of endless repetitions of one letter. Thus a "flush" of, say, spades determines the introduction of a certain letter in a protein "word".

By making different "packs" in which the order of the "cards" were known, the biochemists were able to determine the codes for all the letters of the "alphabet". To be sure, there are still some obscure points. Several "letters", for example, seem to have the same "code name", and conversely, different "code names" sometimes denote the same "letter". In time this will undoubtedly be cleared up. The main thing is that the key to the code has been found.

Imagine that the "protein letter" has been deciphered completely, we have read it to the end and are in possession of the code which nature has been handing down from generation to generation. Knowledge of the genetic code opens up to man the mysteries of the mechanics of life. Man will learn to build proteins—the molecules of life—according to his own desire. He can learn to produce designs unknown to nature. New

proteins can be used to build new kinds of organisms, just as man breeds new species of domestic animals and cultivates crops.

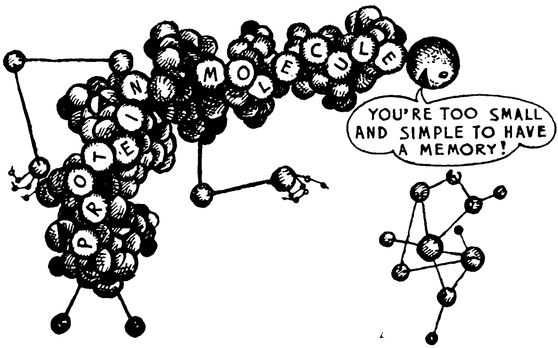
The biologists' greatest dream is to produce life in a laboratory test-tube. Engineers, however, find that this is insufficient. "Let nature cook life in test-tubes," they say. "We'll mechanize the manufacture of living molecules and introduce flow production. Then we'll teach machines to replicate themselves along similar lines."

Machines of Life

The machine capable of replicating itself is still on the level of the now famous cybernetic tortoise which simulates reflex mechanisms. Only it simulates self-reproduction.

It has four different "suits", like a real "cybernetic molecule", which are represented by units with different electrical properties built into the circuit. Current passing through the "suit" units triggers relays in the "cellular medium". The order in which the relays make circuits is rigorously fixed, spades joining only with clubs, hearts with diamonds, and so on. The result is a new "cell", which appears alongside the initial one. It separates and, if conditions are favourable, proceeds to produce a replica of itself. If the environment is made to change drastically, the "molecule" "dies" and disintegrates into its component parts, which serve as "food" for new "molecules".

Scientists are using this ingenious toy to study the living cell and probe its finest mechanisms. The principle may one day be applied to construct machines capable of reproducing themselves.



"Oh, so it is possible," you will say, "and one day we shall have two types of self-reproducing systems: biological and mechanical. To what purpose is this? Why did nature begin by producing molecular structures, which later evolved into living organisms which in their turn developed cybernetic systems possessing qualities like living creatures? Was the human link so essential?"

You know the answer yourself, of course. One cannot compare men and machines. A machine isn't alive.

But why isn't it alive? Why do we say that the complex molecular structures of living matter are "living" while the electronic hardware of semiconductors and thermionic tubes is lifeless? After all, the machines also possess many important qualities inherent in living matter, and one day they may even start replicating themselves.

The secret lies in the component organic molecules of living matter. Firstly, they are very big, giants in the world of molecules. From this stem their characteristic features. Their size ensures

the high stability of their properties. Half of such a molecule can be torn away without affecting its properties, and a protein remains a protein or a carbohydrate, a carbohydrate. If, on the other hand, an inorganic molecule loses some of its components an entirely new substance results. Most important, though, big molecules possess "memory". They can store information and pass it on to other molecules. We already know how this is done: the information is written in a concise and compact code. Small molecules possess no such properties.

Placed in a nutshell, the big molecules which go into the making of living organisms are cybernetic systems. They store information and they reproduce and propagate. Living organisms are not only cybernetic systems on the large or macroscopic scale. Every constituent molecule itself obeys cybernetic laws. For a physical entity to be alive it must possess cybernetic qualities even at the molecular level. That is why a machine built of lifeless molecules is lifeless. It is capable of no more than a schematic simulation of the principles of living processes.

Leningrad scientists used such a machine to investigate their theories of cell division. In Kiev, workers studied the next stage: how an organism adapts itself to the environment, how its further development and growth takes place; in short, they used it to study the mechanisms of evolution.

"Evolutor" was the name they gave to their machine built to demonstrate the processes of survival. Like God in the Bible, the Kiev scientists began by creating "water" and "earth." Their scale being much smaller, they linked the two media under the heading of "environment".

Then they added food. Finally (on the sixth day?) they populated their "world".

Their electronic "world" did not really have a "primordial ocean" or any organic globules of food or amoebas to inhabit it. These existed as conceptual notions. In this respect the approach was even simpler than in Leningrad. In Kiev they even replaced electric circuits with plain numbers.

A computer was duly programmed with specific symbols to denote the habitat, the food, and the population. The "food" was programmed to move in circles. The electronic "animals" were programmed to catch and devour the food. Sixty-four modes of behaviour covering a variety of contingencies were tabulated for the "animals". This, of course, is only a fraction of the potentialities of even the simplest of protozoan animals.

The Evolutor population were not only foragers but breeders as well. They were programmed to breed in the protozoan fashion of cell division. A modification copied from life was introduced into the machine, and the progeny were not necessarily exact replicas of their forebears, either in looks or behaviour. The variations were purely random, some being beneficial, others detrimental. This was made dependent on random changes in the digits of the "behaviour" table. In this way the scientists simulated the most important feature of living organisms which makes evolution possible, namely, mutation.

The Evolutor was switched on and the "struggle for survival" began. The first to perish were the "animals" which trailed the movement of the "food". For the "food" had been programmed to move faster than the "animals". The trailing

"animals" thus could not catch up with the "food" and soon "starved to death". Those moving towards the "food" survived. They multiplied and their progeny adapted themselves to the environment as a result of the natural selection of useful random mutations. They "learned" to close in with the "food" and were always "well-fed". The progeny of these "better adapted" animals gradually improved, squeezing out the less adapted ones. Finally the fittest remained, and the population of the electronic world became uniform. This happened in the sixty thousandth generation.

The electronic millennium came much quicker than on earth. This is hardly surprising, since the Evolutor provided only a very approximate analogue of the evolution of life on earth many hundreds of millions of years ago.

The experiment, it will be observed, was not aimed at "teaching" a machine to reproduce. The idea is that in future machines should be capable of reproduction and improvement—though not of their own accord, but as the result of the incorporation of a suitable programme of operations.

Line-Up of Molecules

A photomicrograph reveals row upon row of molecular palisades made up of protein chains densely spiked with short perpendicular bars. Such an orderly packing of molecules is not unlike a crystalline structure. The picture, however, is of a nerve, or rather a part of its sheath, which is wound around the stem like insulation tape on an electric wire.

Photomicrographs of muscle, fat and other tissues of the body reveal the same parade of molecules arranged in ordered ranks and rows. Such a stratified structure is found in the eye, in the green leaves of plants, within the nucleus of the cell and in the surrounding medium — wherever life pulsates and the vital processes of chemical combination and recombination are taking place.

The discovery of the "crystalline" structure of living tissues came as a surprise to the scientists. If not for the electron microscope we might never have known how carefully we are assembled. It opened up a new window into the microcosm. For centuries scientists were forced to stop short at the threshold of the finer structure of the cell. Now the molecules themselves came within their field of vision. They must have felt like Pinnoccio did when he discovered that the tattered old painting on the wall concealed a door leading into a strange and wonderful world. What magician marshalled the molecules within us into such military order?

The biologists devoted themselves to the investigation of the fine structure of the living organism. Scientific publications were filled with reports of new observations and new details. And everywhere workers observed the mysterious molecular palisades.

They proved to be very delicate. If by some fault or mishap the supply of oxygen and other necessary substances to a tissue was disrupted, the orderly ranks would break up.

On the other hand, if the rows were disarranged, the cells ceased to function and absorb food even though the supply was adequate. It was evident that there existed a definite, and as yet inexpli-

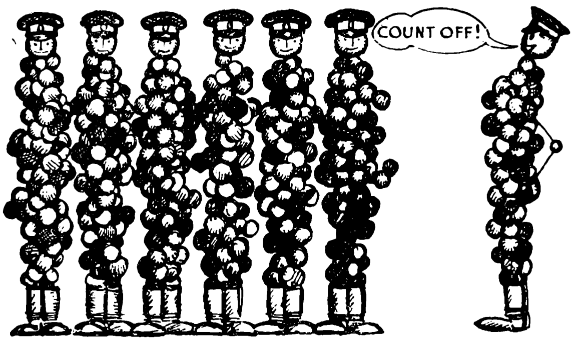
cable, connection between the molecular line-up and the vital functions of the cell. As if someone had ordered, "Molecules, fall in! Commence work!" No order, no work.

In one of his delightful stories, Stanislaw Lem, the well-known Polish sci-fic author, describes the planet Bzhut, which is so small that there is not enough sleeping room for its inhabitants. The resourceful Bzhutians, however, find an ingenious way out. They compile atomic diagrams of every Bzhutian which present an atom-by-atom and molecule-by-molecule picture of his body. When the time comes to go to bed, a Bzhutian squeezes himself through a small door into a body atomizer. There his body is dispersed into atoms which can be tightly packed away for the night. In the morning an alarm clock switches the atomizer on and his body is re-assembled according to the atomic diagram. The door opens and out pops the Bzhutian. He yawns, stretches and goes to work.

The method, Lem assures us, is quite painless and one need not fear that one's scattered atoms will be re-assembled into someone else. At worst, one can be re-assembled.

The Bzhutian scientists, Lem goes on, have found other useful applications of the human (or Bzhutian) atomizer. When a scientist is unable to solve a tricky problem he enters the atomizer and remains there for several decades. If he finds, on emerging, that the problem has not yet been solved, he goes back into the atomizer—until it is solved.

There being no such apparatus on earth, our scientists have had to face up to their problems in a different way. The key to the answers lies in cybernetics. The strict dependence of metabol-



ic processes in cells upon the orderly configuration of molecules is analogous to the relationship between control and effector mechanisms in mechanical automatic devices, such as the steam-engine governor, which regulates the supply of steam to the cylinders, or a ship's automatic steering machine.

The vital functions of the organism are also regulated automatically, and on the cellular level the control units are represented by the elaborate molecular structures observed in the electron microscope. A fault in the structure affects the chemical processes within the cell and these, in turn, affect the molecular configurations.

The secret of the remarkable precision with which the complex of living processes in cells is regulated lies in this interrelationship of structure and functioning. The regulating system is extremely flexible. The intracellular automation is, to put it technically, continuously adjusted to ensure optimum conformity to operating conditions. Thanks to this the organism can adjust itself rapidly to changing conditions and maintain

cellular metabolism at the required level. And there are one hundred million million such perfect automatic devices within us!

But this is, so to say, microcybernetics—the control of the simplest vital functions. Nowadays people specializing in the study of living organisms are turning increasingly to technology for practical advice. Our body, they find, contains a wide variety of living automatic regulators.

Our "Central Heating" System

A healthy body, as we all know, is characterized by a constancy of temperature, chemical composition, blood pressure, etc. Thus, normal temperature is 36.6 degrees centigrade, normal sugar content of the blood is 0.1 per cent, normal blood pressure is 100-140 millimetres of the mercury column.

The organism maintains these parameters at a constant level by means of the system of automatic control called homeostasis. Thanks to it mammals maintain a body temperature constant to within one-tenth of one degree regardless of wide fluctuations in ambient temperature (the temperature control mechanism is called thermostasis). But why, one might well ask, does the body's temperature happen to be at around 37 degrees? This temperature is most suitable for the body's metabolic processes. Nature has taken great pains to achieve optimum temperature conditions for our bodies. To be sure, body temperature is strictly stable only deeper inside. Our hands, feet and skin are much cooler, and in normal indoor conditions their temperature is usually no more than 33 degrees. Nevertheless,

the necessary metabolic processes take place as efficiently as inside the body.

It would be more correct to say that 37° is the temperature at which the body's heat balance is the most stable. Minor deviations from this figure are easily compensated, because, as an engineer would say, the heat input and output is well balanced.

It has been calculated that the body maintains such stable equilibrium as long as the temperature remains above 33° and below 45°. These are the limits observed in all warm-blooded animals. At the lower threshold weather changes make the physiological temperature regulators operate in extreme conditions, so to say. Too high a temperature of the surrounding air also affects the proper functioning of the control system, but in the other direction. In both cases the automatic regulating system may break down. The optimum temperature of 37° is maintained in the organism by means of heat input and output control. The main suppliers of heat to the organism are the muscles, where the body's "fuel" is "burned". Other bodily "furnaces" are the kidneys, lungs and heart. Even a man at rest, when his muscles are relaxed, is quite a source of heat, giving off as he does some 1.6-1.8 million calories to the surrounding air in 24 hours—about as much as a small electric heater. When we work and move about our heat output rises sharply.

The body knows this and if it gets too cold it starts moving spontaneously. When your teeth begin to chatter and you shiver with cold it is a sure sign that your organism is stoking up its furnaces. In fact, the body as a whole operates as an economical, efficient automatic heating unit.

The heat evolved by the muscles and internal organs is carried to all parts of the body by the blood. Heat transfer by conduction directly through solid matter, from muscle to muscle or from stomach to kidneys, would be most inefficient. Our body, the muscles, skin and fats, are poor conductors of heat. The organism has taken this into account, and it transmits heat through the blood stream. When we get hot, blood flows abundantly to the skin and we give off more heat to the surrounding atmosphere. When it is cold, less blood flows up to the skin, and our body heat is conserved.

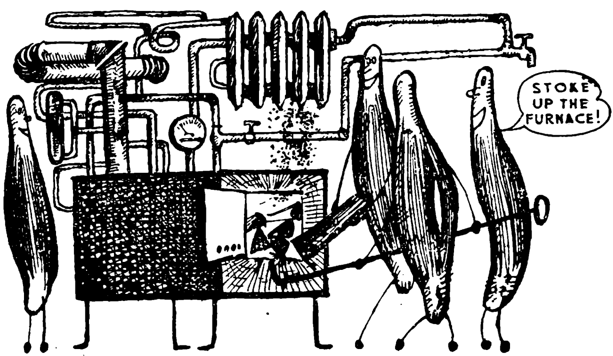
Once a man was cooled in a special chamber to twenty degrees. He was kept in this state for two hours, with calorimeters measuring the amount of heat given off by the body attached to a leg and an arm. Thermometers were placed at nine points of his body to estimate its average temperature. The amount of heat given off through the skin was found to drop sharply, although heat production had increased by twenty per cent.

Many scientists, it should be said, believe that the physiological mechanism responsible for maintaining an even body temperature is on the whole designed for warm rather than for cold climate. Man, they say, is essentially a tropical animal and although he can live in cold climate it is as unnatural as a polar animal living in the south.

The organism has several means of controlling body temperature. One is through the evaporation of water, a process which requires much heat. The organism readily resorts to it when it is threatened with overheating, and a person perspires. In short, everything is most thoroughly

regulated—just as in mechanical systems, one is tempted to say. I once did, in fact, and the physiologists were offended. For, they said, it would be a long time before engineers achieved anything as efficient as the control systems one finds in animal organisms. They heaped data and arguments galore on my head. To begin with, the automatic regulators within us are much more perfect than the best mechanical automatic devices ever built by man. The delicate balance and flexibility of the simplest metabolic regulators inside a living cell are far beyond the capabilities of the most ambitious engineer. This is hardly surprising. The mechanism has evolved and been perfected over millions of years, and at the present time engineers can still do little more than dream of developing something remotely resembling the flexible self-regulating systems created by nature millions of years ago.

Some new and interesting features have recently come to light concerning more complex aspects of control processes. Take temperature control (thermostasis), for example. The organism's



temperature was found to vary with the time of day. At night the body's temperature is lower than in daytime. In the morning it is around 36.5 degrees C, towards evening it rises to 37.5 degrees. Our body's temperature regulators are capable of independently adjusting themselves to environmental conditions.

Incidentally, running a temperature—the conventional indication of illness—does not mean that there is anything wrong with the body's thermostatic system. On the contrary, it indicates that the temperature control mechanisms have readjusted themselves to new operating conditions requiring a temperature of, say, 38 degrees, which is better suited for the organism to cope with the disease. Fever is an indirect indication of illness; it signals that a malignant process is going on in the organism, but it does not mean that anything is wrong with the heat control system.

Doctors sometimes deliberately inhibit the functioning of body temperature regulators. By lowering the temperature they induce a state of artificial "hibernation" in which the vital functions of the organism are slowed down, making it possible to perform operations which cannot be carried out in normal conditions. This is achieved by causing a mild paralysis of the nerve centre which controls our "heating system".

And this brings us to the main point, namely, that thermostasis is a function of the nervous system. Not the central nervous system over which the cerebral cortex presides, but the local, autonomous system which operates automatically and independently of the conscience.

The temperature control centre is located in the myelencephalon, or afterbrain (*medulla oblon-*

gata), which is a continuation of the spinal cord. It is washed by an abundant flow of blood which keeps it continuously informed of the state of the body. It regulates the flow of blood to different parts of the body and increases or reduces the flow depending on whether more or less heat is needed. This has been traced in detail in experiments on animals. When a stimulus was applied directly to the thermostasis nerve centre dogs behaved as if it were hot in the room, their tongues lolled and they panted heavily. A "cold" stimulus caused them to shiver.

But temperature changes usually come from the environment, and it is natural to expect the body to have thermal sensors at its extremeties. Such sense organs, called receptors, have been found all over the skin. Some receptors respond only to cold, others to heat. Every receptor is connected by a thin thread of nerve to the control centre. They relay a continuous stream of information to the control centre. When the "cold" receptors report we feel cold; when the "hot" receptors fire we feel warm. The control centre analyses the information and issues the necessary commands: "More fuel to the muscles! Switch on additional heating units!" Or: "Shut off flow of hot blood to the skin! Economize, no wasting of heat!"

Our heating system is a very sophisticated arrangement in which the sensory elements act directly on the temperature regulator. The mechanism is very sensitive and goes into operation a few seconds after the temperature of the outside air begins to change. In a healthy body it never lags.

A detailed study of the heat receptors in the skin revealed that they also register the rate of change

of the outside temperature. The thermostatic system responds accordingly with greater or less alacrity to restore the equilibrium.

It obviously took nature a long time to attain such perfection and precision. Temperature control in the lower mammals is not so precise, and fluctuations of body temperature may be as much as one degree.

But how, one might ask, do insects, lizzards, frogs and other cold-blooded animals get along without "internal heating"?

Beehive Cybernetics

Nature found a clever way out when it arranged the life of communal insects. Although a beehive has no heating system a fairly even temperature is maintained inside, ranging from 35 degrees centigrade in summer to 25-30 degrees in winter. It is regulated by the bees themselves.

Thus, if the hive gets cold the bees start buzzing—which is to say that they vibrate their wings very rapidly. This serves to raise the temperature of their bodies a little. To keep the warmth from dissipating they crawl together and cover the cells containing the larvae.

The procedure is more complicated when the hive gets too hot. Some bees start carrying water in their proboscises, some spray it inside the hive, some beat their wings to create currents of air and make the water evaporate faster. In the evaporation of water, we know, heat is expended, and the hive cools.

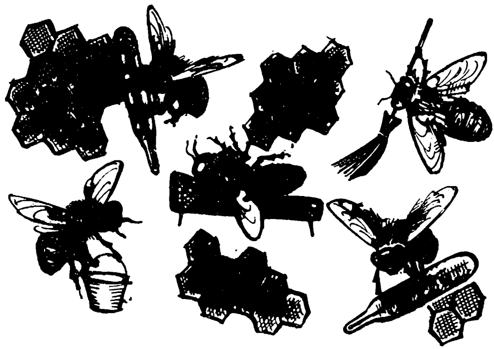
This elaborate organisation in bee colonies is analogous to the homeostatic control of body processes in higher organisms. In this respect a

beehive as an entity can be treated as a living organism.

Every bee carries a heat-sensitive element in its body which responds to temperature changes of as small as 0.2 degree centigrade. The most interesting feature is that the sensory elements are tuned, as it were, to the temperature of 35 degrees above zero, the most favourable temperature for the bees' vital functions and the development of the larvae. One could say that there are thousands of living thermometers in all parts of the hive which both measure and control the temperature. The temperature control can be effective only if there is complete cooperation and understanding among the water-carriers, sprayers and "ventilating" bees. This is achieved by means of an elaborate division of labour. Every bee has her specific tasks in accordance with her age (only female bees do work). A young worker usually spends the first three days of her life cleaning the honeycombs. Then she works for about a week as a nurse, bringing up the young and doing incidental repair and construction work. Gradually she spends more and more time at the entrance to the hive, collecting nectar and pollen from the forager bees. This, as a rule, soon becomes her permanent job.

But the labour demand varies with the season: in summer there is a lot of work to do, in winter "business" is slack. The demand is further affected by the weather and the size of the community. Nevertheless, the necessary number of bees is always on hand for forageing for water or nectar or building new honeycombs.

A colony of bees was once divided in such a way as to leave only foragers in one half and "housekeepers" in the other. The bees adjusted



themselves to the new circumstances, and soon both families had all the required trades.

Who regulates and distributes the work in a beehive? The German entomologist Martin Lindauer once marked a bee and for many hours traced her movements. He used his observations to compile a "time and motion study" form. Lindauer drew a little broom when the bee was engaged in cleaning the comb; a tophat and cane when it was making the rounds of the hive; a couch when it rested. To his surprise he found that the symbol that occurred most frequently was that of the couch. Bees, it appears, are not half as industrious as they are credited to be. True, work in the hive goes on day and night, which accounts for their frequent naps.

When a bee finishes a job she "patrols" the hive. She makes several rounds of the honeycombs, looks into cells and sees how things are going in different parts of the hive. If she finds a vacant working place she fills it at once. Thus bees do not have to be "told" what to do. They find out for themselves.

"In addition to the thousands of patrol bees crawling all over the honeycombs," Lindauer writes, "there is a large reserve of 'loiterers' waiting for a rally call, as when a rich source of food is discovered."

The information is delivered by means of a special communication system. A forager bee that has found a meadow filled with blossoming flowers performs, on her return to the hive, an intricate dance. Other bees troop behind the dancer and then fly off in the indicated direction to look for the food. The "language" of bees is a sign language.

To sum up, bees measure the temperature inside the hive and determine how much food the larvae need and how many new cells should be added to the honeycomb. They work accordingly as water-carrier, forager, nurse or builder, as the need arises. Thereby a high degree of flexibility is achieved in regulating the life of the family. The general pattern of life inside a beehive resembles the operation of a cybernetic system.

"The engineer, of course," Lindauer writes, "will regard this system of control and communication as rather primitive."

It also falls for short of the speed and accuracy with which the nervous system handles information. Thus, it takes anything from fifteen minutes to half an hour for the "news" of a water shortage to reach the hive entrance from an overheated centre. Nevertheless, beehive cybernetics is an illustration of the variety of control methods found in living nature.

At a meeting on biological cybernetics in the spring of 1962, I heard Professor Valentin Nesterov speak on "forest cybernetics". Every day for several years Professor Nesterov measured the

humidity and temperature of trees and plants and the surrounding air. He found that many plants kept their heat and moisture content at a fairly even level in rainy and hot seasons. Some plants are more successful in this than others. Foxberry and wheat, for instance, are good self-regulators; mosses, fungi, flax and potatoes are practically incapable of regulating their internal states. They grow sodden when it rains and shrivel up in the sun.

"Vegetable cybernetics" is even more primitive than the cybernetics of the simplest animal organisms. I mention this because the cybernetic devices within us, too, are of various degrees of complexity.

Body Communication Systems

Nature has certainly taken great pains to avoid making man too sweet, for the sugar content of 100 grams of blood is only 80 to 120 milligrams. This, of course, is not ordinary sugar. It is called grape sugar or glucose, and it is an important source of energy for our organism. When it oxidizes, usually very slowly, it turns into water and carbon dioxide. The energy evolved in the reaction powers the chemical "factories" in the cells of body tissues.

Delays in fuel delivery interfere with the smooth running of intracellular production processes. Especially sensitive to fuel shortage are nerve and muscle cells and even small delays in supply can lead to grave disorders affecting the whole of the organism. Therefore the sugar content of the blood, which is the body's main fuel transport system, must be kept at a constant level.

The organism quickly takes steps to counter any difference between the sugar required and that delivered by the blood.

The main sugar distribution centre is the liver, which is one of the body's fuel storage depots. In the liver glucose is stored in the form of a complex animal starch called glycogen. When fuel is to be delivered to working cells the glycogen disintegrates into the simpler molecules of glucose. The cells continuously absorb glucose from the blood, "burn" it and clamour for more fuel. The liver is kept busy making glucose out of glycogen, the stocks of which are replenished with glucose taken from food entering the body.

At first glance the liver's job seems to be rather futile, what with extracting glucose from the blood and turning it into glycogen, only to reconvert it into glucose which goes back into the blood. This, of course, is not the case, and there is a deeper meaning in these endless conversions and reconversions. They constitute a recycling process within the living organism, a process which is essential for life and by means of which the required chemical composition of the body is controlled automatically by the liver.

So here we have another living self-regulating system provided by nature. The liver, it should be noted, has no nerves joining it with body cells, nor is the body equipped with nerve receptors for measuring sugar content. How, then, is it regulated?

In order to function efficiently as a fuel dispatcher the liver must be able to decide how much sugar should be added to the blood and how much should be stored away for future consumption. The necessary information for this is conveyed by the blood. The liver lies at a cross-roads of

blood routes. Blood from the intestines passes through it before joining the main stream and reports how much sugar has been extracted from food. On the other hand, the liver is washed by blood coming from the muscles and internal organs, and this tells it whether they are adequately supplied. Thus it is the sugar content of the blood itself that guides the liver in its control functions. The relevant signals are transmitted not along nerves but by the blood. This is effected by special chemical substances which act as messengers. They do not participate in the chemical reactions and the messages they carry are the signals for converting glucose into glycogen or glycogen into glucose.

One could expect this function to be carried out by a single substance, or at most by two substances of opposing action. Actually there are six messenger substances in the blood. The pancreas, for example, secretes insulin, a hormone which reduces the amount of sugar in the blood. The suprarenal glands send out several simultaneous "messengers" which counteract insulin—they are its antagonists. One of these appears only when urgent interference is required. Finally, another participant in the organism's complex messenger service is a substance secreted by the thyroid gland. It acts as a general intensifier of metabolism and it also makes the main "sugar dispatcher", the liver, work faster.

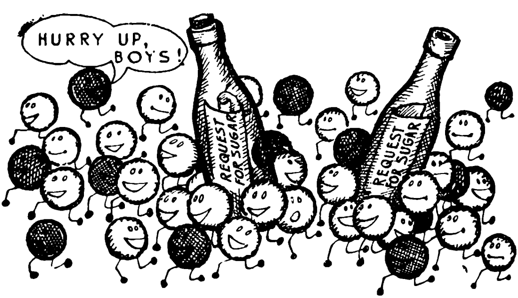
You see that the organism is well staffed with messengers for transmitting commands from one organ to another. Why does it duplicate the work of the messengers tasked with the duty of informing the liver that sugar should be added to the blood? To one messenger responsible for delivering an order to reduce the amount of sugar

there are five messengers for ensuring an increase in the sugar content.

There is good reason for this. The organism can stand a temporary increase of sugar with hardly any ill effects. A shortage, however, is most distressing. For this reason the organism has taken special precautionary measures to be sure of countering a dangerous fall in sugar content.

Scientists have also found that the glands responsible for dispatching the sugar messengers act on orders "from above". Their "boss" is the hypophysis, or pituitary body, an endocrine gland lying at the base of the brain, one of the functions of which is to control the sugar content of the blood. The pituitary body is in turn controlled by a nerve centre which specializes exclusively in regulating sugar delivery and expenditure. It is located in the diencephalon, or midbrain, next to the thermostasis centre.

The midbrain is connected with the pituitary body by nerve fibres which transmit commands to the latter and it is kept posted of events by messenger hormones secreted by the endocrine glands and the pituitary body which are brought to its nerve centres by the blood.



The circle is closed: the midbrain, which issues commands for the distribution of sugar in the organism, is kept informed of the fulfilment of the command. In this circle, or feedback loop, as an engineer would call it, the signals are transmitted by nerves and chemical substances.

The chemical communication system is inferior to neutral communication. The latter works like a telegraph; the former is a kind of "bottle post" in which messages are sealed in bottles and cast into the stream, like shipwrecked sailors do. The pituitary body acts as an intermediary between the nervous system and the organism's power plant. It receives orders from the nervous system and passes them on to the glands which control the blood's sugar content. To continue our analogy, it is the pituitary body which reads the "telegrams" transmitted by the nerves and bottles the relevant messages. The bottles drift downstream to the addressees. This, naturally, takes longer.

Why does the organism employ such a comparatively primitive communication system? The reason is that it is not the speed of the response but the duration of the stimulation that is important here. As long as the hormones are in the blood they are doing their job. A nerve signal arrives faster, but it disappears as soon as the message is delivered. A continuous stream of signals would be required for the liver to continue its work of converting starch into sugar. A continuous stimulus is better suited for ensuring steady equilibrium.

The two means of communication complement one another, and where it is necessary messages are transmitted by the faster and more reliable "telegraph" system. At some point they are picked

up by the slower messengers who deliver them directly to the addressees—and stay on to see that the commands are carried out.

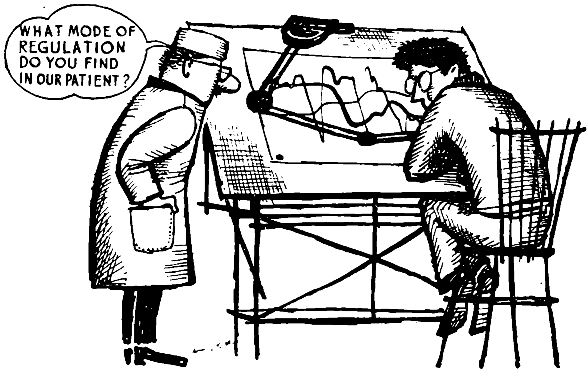
Living Automation

Nature, we see, has evolved a complex structure for the sole purpose of regulating the concentration of a single substance, sugar, in the blood. Our bodies possess a great number of other kinds of automatic regulators. The heart and lungs are also self-regulating mechanisms which maintain optimum performance under varying conditions.

The more one reads of the various automatic devices packed by nature into our bodies, all working to keep body processes in perfect balance, the clearer one comprehends the true meaning of Ivan Pavlov's words: "Life as a whole, from the very simplest to the most complex organisms, including, of course, man, represents a long series of increasingly complex equilibrium responses to the environment."

Today the idea expressed in these words has taken on added technical meaning. Not only because a comparison with automatic control system offers a graphic picture of the working principles of living "mechanisms". An engineer's approach to biological phenomena offers an entirely new insight into the working of our body's automatic control systems. He can plot response diagrams, calculate the time required for a readjustment, and trace just how it is effected.

In one experiment a man was given successively 25, 50 and 100 grams of glucose with his food. The blood's responses in the shape of its



sugar content were plotted on a diagram. The doctors found that in all three tests the characteristic curve was of the same type: a sharp upsweep followed by a series of smaller and smaller oscillations around the normal level.

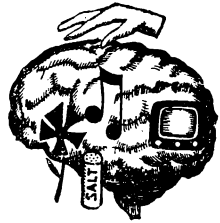
When, in another subject, the responses of the pulse to certain stimuli was tested, a different kind of curve was recorded: following a steep upsweep it sloped gradually down to the normal line.

Many experiments were carried out. For example, in some the composition of the blood or the inhaled air was disturbed artificially, in others the body's moisture content or temperature was varied. In all cases the graphs revealed that the body's control systems responded in one of only two possible ways to the applied stimuli: overshoot followed by damped transient periodic oscillations (as with the first patient) or irregular nonperiodic oscillations (as with the second patient).

An examination of a great number of people has conformed the existence of these two basic

modes of control of internal body processes. Furthermore, the response characteristic of a given organism holds for each of its individual organs. This is very important, for if one knows the way in which the organism controls the internal processes, then this can be utilized when prescribing a cure for a fault in one of the body's control systems.

Such diagrams as described above can be used to evaluate the quality of the body's control functions. For example, if the artificially increased sugar content of the blood reverts to normal in thirty to fifty minutes, a person is healthy and his sugar regulator is in order. But if it takes more than an hour to restore equilibrium, the organism is said to be in a metastable condition, and the slightest external stimulus may disrupt the work of the sugar-control mechanism. This means that prophylactic measures against diabetes should be taken.



III. LABORATORY OF THINKING

Mapping the Brain

My acquaintance with the living brain, that mysterious laboratory of thinking, began with a map. Not an ordinary one, although like a map of the globe, it was divided into two hemispheres. It was marked with little circles, triangles and lines to denote various "features of the relief". There were large, smooth plains cut through by deep fissures and mountain ranges. There were deserts and densely populated areas. In some the inhabitants were short and stout, in others they were lanky and thin. A mysterious and poorly explored world with a population of some fourteen thousand million nerve cells, or neurons as they are commonly called.

As I thumbed through this remarkable atlas there arose before my eyes vivid scenes from the centuries-old history of exploration of that wonderful world, in whose depths are born poetic symbols and the orderly ranks of mathematical formulas, music and logical reasoning, great ideas and the whole gamut of human emotions.

The oldest maps in the atlas date back to Byzantine, Arab and Medieval sources. Wavy lines divide the brain into three parts. Like the ancient Greek temples of justice which consisted of three halls, one for establishing the truth, the second for pronouncing justice, the third for carrying it out, the scholars of yore divided the brain into three main compartments. In one resided fantasy and imagination. This was the receptacle of the emotions. In the second resided the intellect. It was where thoughts and ideas originated. The rear compartment housed the memory and controlled body movements.

All this is undoubtedly very primitive, but it represented a first attempt to offer a scientific explanation of the role of the central nervous system. It was a step forward from notions of the heart as being responsible for our emotional and mental activity and was at least as revolutionary as the rejection of the idea that the Earth was supported by three whales. However naive the ideas of the first explorers of the Earth concerning distant lands, in the final analysis they were immeasurably closer to the truth than the most detailed descriptions of the elephants or whales that were supposed to be carrying a pancake-shaped earth on their backs. At a time when sailors and travellers were preparing to circumnavigate the globe and cross continents, the explorers of the *terra incognita* of the brain were paving the way for decades of pioneering explorations and bold research.

It is common for discoverers of rivers and mountains to leave their names on the map of the globe. The map of the brain also carries the names of many a first discoverer: Rolando's fissure, Betz cells, Lissauer's zone, Darkshewitsch's nucleus,

several neural structures named after Bekhterev, the Sylvian aqueduct, pons Varolii, and so on and so forth.

Early explorers of the brain had no idea of the functions of its fissures, gyri, convolutions and other structures. One of the first questions they asked was whether a man's talents and character were in any way reflected in the depth or curvature of the folds in his grey matter. The German Wagner was one of the first to study the brains of deceased scientists. They were surely more talented and more intelligent than the ordinary run of mortals, he reasoned, and this should show up in the brain. He was disappointed, however, for he could find nothing out of the ordinary in the cerebral topography of outstanding minds. Maybe the weight had something to do with talent? Wagner compiled a table. It was headed by Cuvier, not far away came Byron. But what about the unknown madman whose brain was just as heavy as that of the great poet?

There have been many attempts to detect a link between a person's abilities and the size of his brain. In Paris a group of scholars set up a society dedicated to the purpose of studying the brains of different people. Each bequeathed his brain for the others to study after death. This rather ghoulish covenant was faithfully carried out, but its results were nil. One of the most convincing refutations of the very notion of any connection between talent and cranial capacity is to be found in a table with Ivan Turgenev at the top and Anatole France at the bottom with a brain only half the weight of that of the Russian author. Clearly brain capacity and convolution pattern are not measures of talent.

In Moscow there is a research establishment, appropriately called the Brain Institute, which engages in the most comprehensive study of human and animal cerebral anatomy. I spent many days there, visiting its laboratories and speaking with its workers.

In the first laboratory the brain is studied anatomically. It is taken to pieces in the same way that a child takes a toy apart to see how it works. The thin outer layer is the cerebral cortex. Beneath it lies a thicker smooth layer of subcortical white matter, followed by the mesencephalon, which merges gradually into the spinal cord. Part after part is removed until the whole living mechanism is exposed, down to the shiny white "wires" of nerves which join the brain with all parts of the body. The tangled network is not unlike the mesh of wiring one sees inside a radio set. The parts are photographed, described in detail and entered into anatomical charts and atlases of the brain.

In the next laboratory the brain is cut with a special knife called a microtome into twenty or twenty-five thousand thin, semi-transparent microscopic sections, stained with dyes and mounted on glass slides. Staining is a procedure which utilizes the property of different cells and tissues to react differently to dyes in order to bring out their fine structure. The stained sections are subjected to a thorough microscopic scrutiny which reveals the internal structure of the brain. I was shown a remarkable file containing thousands of photomicrographs and drawings of the fine structures of the brain. It takes infinite patience to study each slide, observe similarities and differences between various cells, gain an understanding of the laws governing their

distribution, finally simply to count them in order to produce new charts showing the cytoarchitectonics, or cellular composition, of the brain.

It is not easy for the uninitiated to see the difference between various charts; the innumerable smudges, pockmarks and whorls on the bright-orange background seem so alike. Yet an expert need but glance at it to say that this section is from the occipital lobe and that one is from the frontal lobe.

"Observe that in the parietal lobe the cells are small and densely packed; they look like sprouting seeds," my guide said as he showed me several sheets that looked like abstract art. "Here the picture is quite different. The cells are bigger and more widely spaced. This is the motor area. But these things can be understood better in the next laboratory, which studies individual nerve cells."

The "next laboratory" was cluttered up with pictures of neurons; they hung on the walls, sprawled on desks and teetered precariously in stacks on chairs and window sills. The numerous enlarged photographs gave the room an appearance of a photographer's studio. Here each little neuron, which is seen in the microscope as a small fuzzy star, is blown up to the size of a big spiked sun. The neuron is frequently compared with a tree, although I do not think the comparison is a happy one. The gossamer thread of nerve, called the axon, growing out of it hardly resembles a tree trunk. And the scraggy body of the cell with its tangle of short, fuzzy branches (the dendrites or processes) is more like some fantastic shrub.

The Brain Institute possesses a remarkable gallery of neuron portraits. Here are the pyramidal

cells, whose unusual shape and size immediately strike the eye; they were among the first to be discovered, almost a century ago, and are especially numerous in the areas associated with body movement. Here are neurons which look like snowflakes. They fill the spaces between the bigger pyramidal cells, barely touching them with their delicate dendrites.

I was shown a "family album" with enlarged photographs of neurons arranged just as they occur in the brain. The manufacture of such a "group portrait" of neurons is a difficult job. Each neuron must first be drawn with the help of a special enlargening device attached to a microscope. It may take a whole day to draw one neuron. When the component pictures are ready they are placed on one sheet and fitted together into a kind of photographic montage. This is how new and more detailed maps of the brain are drawn. They bring the invisible landscapes of the brain within reach, just as a powerful telescope offers a close-up of lunar craters.

Today it is generally accepted that neuron structure determines the functions of the various parts of the brain. One of the first parts of the brain to be associated with specific functions was the area around the central fissure, which crosses the brain laterally. In the nineteenth century scientists observed that stimulation of parts of this area with electric current caused muscles of the face, head, hands, feet and body to twitch.

A projection of the body on a map of the brain appears to be "upside down". In the lower part, near the frontal lobe, lie the centres responsible for movement of the head and hands. Those responsible for the feet and torso are located higher up, at the parietal lobe. Furthermore, the

right hemisphere of the brain controls movements in the left half of the body and the left hemisphere controls the right half.

The endings of the optic nerves are located in the occipital lobe, in what has been called the visual centre of the brain. The acoustic centre is located in the temporal lobe. In the parietal lobe, next to the motor area, is an area joined by numerous nervous tracts with various parts of the skin. It is responsible for temperature, pain and tactile, or touch, sensations.

All our senses are represented in the central nervous system, though the terminals of the taste, or palatine, nerve tract from the tongue and the olfactory nerve tract from the nose have not yet been found. They come within the temporal lobe, but the specific neurons associated with them are still not known.

Neither the sensory nor the motor centres are uniform in themselves. In the motor area, for example, there are sections which control complex motions involving the contraction of several muscles, as in turning the body or chewing, for example. The areas responsible for various functions (and they usually differ in neuron structure and pattern) have been numbered for convenience.

Thus, if area 17 is stimulated a person sees sparks or glowing spheres. The neighbouring areas 18 and 19 respond with more complex optical images, like coloured rings, figures of animals and contours of objects. These two areas are responsible for the higher optical functions of seeing, while 17 is responsible merely for the perception of optical stimuli.

The functions of all the areas have not yet been established completely and even the number of areas is debatable. The problem is an important

one and on it will depend our knowledge of the functioning of the brain.

Some scientists have sought to divide the brain into as many regions as possible, their maps containing as many as 200 areas, more than 60 in the frontal lobe alone. They subdivide area 18, mentioned above, into several smaller areas, one of which is even made responsible for drawing talent. So fine a division is reminiscent of the discredited science of phrenology whose founder, Gall, attempted to locate on the skull regions associated with haughtiness, wit, love for children, or thievery.

Other workers went to the opposite extreme of broadly dividing the brain into motor, auditory, optical and several other areas. This approach, too, is not in keeping with the newest scientific concepts.

The brain is best divided into some 50 areas, as is done in fact on the charts of the Moscow Brain Institute. Such a classification is supported by features of the brain's cytoarchitectonics, or neuron structure. The mystery of musical talent, inclination to mathematics, artistry or love of chess is probably to be found in the structural peculiarities of different areas.

The boundaries of all 50-odd areas have been delineated, their surfaces calculated, their interrelationships determined, and the features of area distribution studied for widely different types of people. These studies, however, give an insight only into the superficial structure of that highly sophisticated natural laboratory of thinking. What about the mechanism of thinking itself?

It is the hope of doctors to restore motor ability to disabled limbs. The brain regulates our movements by means of electrical impulses called action potentials. The idea of conducting them from the brain to, say, an artificial arm does not seem at all unreasonable. All a person would have to do then would be to mentally move his arm—and the artificial limb would move as if it were real.

An interesting method of treating paralysis has been suggested. Action potentials from a healthy person are conducted to a patient's paralysed arm. When the "donor" bends his arm he makes the patient's arm bend at the same time. At first the paralyzed muscles respond with difficulty, but gradually they return to normal and can function independently.

Soviet scientists have built artificial limbs controlled by action potentials from the brain; they have been described in detail in special literature. A more recent invention is the so-called motor stimulator for treating paralysis with the aid of muscle action-potential "donors". Not all cases of paralysis can be cured in this way, of course. The method can be applied to help the motor areas of the brain to regain control of arm or leg muscles only if the disease has been detected at an early stage, when the fault in the control mechanism can still be repaired.

One can hardly overestimate the importance of motor activity to the body. It is man's means of locomotion and action upon the environment, his means of changing and transforming it. Knowledge of the mechanisms which control our motor activity is therefore of tremendous importance.

How does one bend an arm, walk, run, swim or do a piece of work? What processes take place within our muscles? How do they receive their "commands", and from whom? Many such questions have been answered by Professor Nikolai Bernstein, Corresponding Member of the Soviet Academy of Medical Science, who has devoted a lifetime to the study of the mechanics of body motion. One of his first papers on this subject was published in the nineteen-twenties. Since then Professor Bernstein has been continuously investigating the problem of *biomechanics.*

"How long have you been studying cybernetics?" I asked him.

"Why, almost all my life," came the unexpected reply. "The study of 'feedback', the bedrock of modern cybernetics, began way back in the twenties and thirties.

"Suppose you prick your finger accidentally. You feel pain, as the pinprick has irritated the muscle, or rather a nerve ending which transmits the stimulation to the brain. It is known that nerve tracts connect the brain with literally every single muscle fibre.

"The pinprick signal travels along the sensory or afferent nerve tract as it is called, to the brain, which then sends a command down a motor or efferent nerve tract for the muscle to react. The whole process is almost instantaneous and you pull your hand away the moment you prick it. The motor response to the initial stimulus is such as if the stimulus were reflected from the brain, and it is called a *reflex.*

"Reflexes as such were known to ancient physiologists. Much later they were more or less accurately described by Descartes. But Descartes and later workers invariably treated reflexes

as open neural loops. When I undertook to develop an equation of motion, however, I found that something was lacking. For the brain must know how its commands are being carried out and what has been accomplished as a result of every successive action. Without such knowledge it would be impossible to go on with the action as the brain would never know whether the previous movement was completed or not.

"In other words, a reflex is of necessity a closed loop, a characteristic feature of all control processes. I first expressed this 'cybernetic' principle of feedback in body motor control in 1934. We did not know the word 'cybernetics', of course, and spoke simply of control in living organisms."

The idea of cybernetics within us thus appears to be older than cybernetics itself! And I find it hardly accidental that Professor Bernstein was among the first workers to suggest that motor control in the human body is based on closed-loop feedback. For Professor Bernstein is not an ordinary physiologist or an ordinary physician. He is a biologist with a flare for mathematics. Witness his work to develop an equation of body motion.

"Did you study mathematics at the time?" I asked him.

"It was knowledge of mathematics that enabled me to arrive at the conclusions just mentioned. It was a platform from which I could view well-known phenomena in new perspective. A mathematical approach offered an escape from the narrow anatomical view of things. When it became apparent that we were confronted with control processes governed by mathematical laws, we knew that there must surely exist an

appropriate control mechanism. We looked for it, and we found it."

It is hardly fair to ask a person to speak of his life's work in a few words. I did the next best thing and went to Professor Bernstein's lectures. I felt myself a student again as I hurried to the old University campus, this time past my own Journalist Faculty, to the department where psychology seniors attend lectures on the physiology of motion.

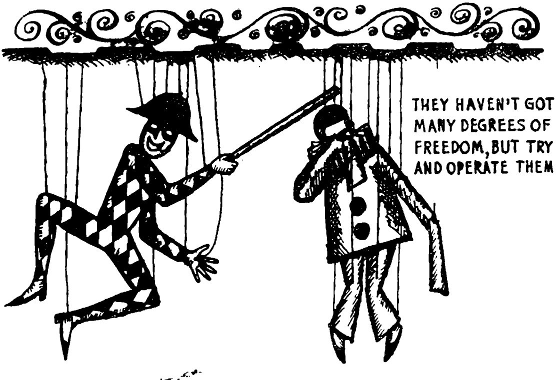
Professor Bernstein began his lecture by inviting volunteers to take part in a simple experiment to demonstrate the principles on which the mechanisms controlling the motion of our hands are based.

"Take this ski-pole," he said, "and fix the top end to the buckle of your belt. Tie this weight of four or five pounds and these two rubber tubes to the ring of the ski-pole. Now take hold of each tube, go up to the blackboard and trace the outline of the square drawn on it with the tip of the pole."

The auditorium burst into laughter as the student floundered with the simple mechanism.

"It's not so simple, after all," the professor said with a smile. "Yet this is a model of one of the simplest motor mechanisms of the human body. The ski-pole represents an arm bone, that is, one joint with only two degrees of freedom. The rubber tubes represent the antagonistic muscles, a flexor and an extensor, which move the 'limb' in the allowed directions.

"You have just seen how difficult it is to manipulate this 'one-bone limb' with two 'muscles'. Yet our body has 639 muscles and 206 bones, and the possible degrees of freedom are expressed by a three-digit number. In comparison, the most



intricate modern automatic machines have no more than four degrees of freedom."

A real arm has seven degrees of freedom. Six, it should be known, are sufficient for any desired movement, which means that the arm can move about as if it were in no way joined to the body—with one degree of freedom to spare!

You might think that the number of controllable degrees of freedom is not such an important thing. But here are two examples.

A ship on the high seas possesses two degrees of freedom, forward and sideways. In practice only the forward direction is essential for steering. If the ship deviates from its course it need not return precisely to the old path but can proceed on a parallel course in the same general direction.

Driving a car is a much more complicated affair. One must follow the narrow lane of a highway, looking out for other cars, the roadside and turns. Automated car driving presents many difficult problems, and no attempt has yet been

made to build an automatic car driver, although automatic helmsmen and pilots have long been conventional on ships and in aircraft. Yet only one more degree of freedom is involved. Imagine the brain's job with hundreds of degrees of freedom!

It is not easy to co-ordinate all the motions our arms and legs are capable of, given complete freedom. Coordinated motion consists, in effect, of supressing surplus degrees of freedom, as a result of which the arm or leg is converted into a controllable mechanism. How is the control effected?

Almost three centuries ago, the Frenchman Galien performed a simple experiment now treated as classical. He pinched the leg of a decapitated frog, and the frog jerked it away. The obvious conclusion is that the brain has nothing to do with the motion. This appears to be the case, and we do say that the involuntary reflex motions known as unconditioned reflexes are quite automatic. Nevertheless, the motion must be controlled by some centre, and it was traced to the spinal cord. If the frog's brain is left intact while the spinal cord is severed, it will not withdraw its leg no matter how great the provocation. The control loops of such simple motions have been traced in great detail.

A motor nerve, which carries commands to the muscle to contract or expand, branches at its terminal end. Each branch terminates in a thin lamina attached to the muscle fibre. Its function is to amplify the nerve signals carrying the command to the degree necessary for the required movement to be performed.

Interspaced between the muscle fibres are elongated spindle-like nerve structures called pro-

prioceptors. Proprioceptive sensory nerve endings have also been found in the joints and tendons. These nerves keep the brain informed of the positions and states of our muscles and joints. They are responsible for *kinesthetic feedback*, which tells the brain to what extent its commands have been carried out.

Kinesthetic feedback is adequate to perform automatic, involuntary motions. For voluntary action, however, this is frequently not enough. Even in performing simple tasks one must see one's hand in order to judge its distance from an object, that is to say, the brain requires visual information. When one feels something the sensory nerve endings supply tactile information, and so on.

The complex control system involves practically all our sense organs, including equilibrium, smell and even our sense of temperature. Taste is probably the only sense which the brain doesn't use to determine the body's position in space, and this may mean nothing more than that we just haven't yet traced a nerve tract from the tongue to motor cells in the brain.

But suppose that all the necessary information were directed to the cells of the spinal cord which make the muscles contract. Estimates show that they would never be able to "digest" all that information. They would be "overstimulated", the result being prolonged and powerful flexion of the muscles, cramp, in other words. That this doesn't happen is due to the fact that the information from our sense organs is delivered to the appropriate areas of the brain.

The organism is remarkably well-equipped with a variety of signalling devices. They can be found, as we have seen, directly inside the motor

units themselves (muscles, tendons, joints) as well as in the body's main "control tower", the head. An elaborate monitoring system, something like closed-circuit television, keeps the brain informed of events in all parts of the body. With this information it is able to exercise its supreme command over body movement.

When the sensory nerve tracts were traced they were found to reach the central part of the brain in a rather roundabout way, through the medulla, diencephalon, mesencephalon and cerebellum. On the other hand, each of these parts of the brain is joined by nerve tracts to the motor neurons of the spinal cord. It thus appears that our motions are controlled not by a single closed circuit but by a multitude of neural loops, by a multitude of superimposed automatic control units and regulators.

When a person begins to learn a new type of motion, riding a bicycle, for example, the requisite information from all the peripheral signal outposts is channelled directly to the brain. It is virtually flooded with information that must be processed. As soon as the brain has sorted out the abundance of data it delegates control over specific movements to the various control mechanisms of the nervous system. The simpler tasks are assigned to the lower sections of the compound control system, and neurons in the spinal cord, for instance, control the methodical contraction of the leg muscles. Higher sections get more difficult assignments. One of the main neural control circuits, which receives information from the eyes and the body's balance centre, is responsible for keeping the bicycle and the rider upright. The brain leaves to itself general supervision and conscious action, which in the case

of a cyclist would mean keeping to the road and steering clear of traffic.

An important feature of this process of learning is that the brain gradually assigns increasingly difficult tasks to the lower automatic regulators, thereby relieving the upper storeys of the more "menial" tasks. The result is that more and more processes are subjected to automatic reflex control, and when this happens one proudly declares: "Well, I have learned to ride a bicycle at last and I don't have to think of keeping my balance any more."

Professor Bernstein has devoted many years to studying the ways in which sportsmen and workmen master new movements. The brain, he found, always seeks to get rid of tasks which do not require mental effort. In this respect it is similar to the "modern" approach to labour; as in technology, automation frees the brain for creative work.

When the analogy between technological and biological automation became apparent the physiologists began to probe the organism for deeper similarities. Engineers know how technical control systems operate. How do the regulators of motion within us work?

Basically, any automatic self-governing system must contain: a motor, or effector, which drives the object being controlled; a sensor for measuring the amount of adjustment (control) required; a sensor for measuring the amount of adjustment actually attained; a unit for analysing the incoming information from the sensors and translating this into commands; and finally a regulator unit, which utilizes these commands to control the motor. In this way the required adjustment is obtained in the required manner.

Let us see what elements of this system are to be found in the human body. The effectors—our muscles—have been studied in great detail. There is less clarity concerning our body's measuring instruments (sensors or receptors), although they too have been studied in considerable detail. The message-to-order inspection system and the motor control mechanism have not yet been discovered. How they work and what they look like is not known, though scientists are quite sure that they must exist, probably somewhere in the neighbourhood of our central control department, i. e., in the upper regions of the brain.

Telephone Exchange?

We have spoken so much of the body's "supreme headquarters", the brain, that it is apparent that we have before us an intricate mechanism resembling—but what?

You prick your finger or accidentally touch a hot iron. The brain receives the information and causes the relevant muscles to contract. This, we know, takes place quite automatically. As if the external stimulus had pressed a button in the brain. That in fact was how many nineteenth-century physiologists pictured the sequence of events. They saw the brain as a kind of control console studded with neuron-buttons. Push one—the elbow joint flexes; push another, it straightens out. As if someone were playing on a keyboard in the brain.

Today this notion appears as a gross oversimplification, for we know that even the simplest motion requires a muscle control unit, an inspection unit and a host of other equally complex

elements and devices. Still, in its time the concept of the brain as a single, smoothly functioning mechanism was correct and progressive.

"The idea of the mechanical nature of the brain, irrespective of these or other conditions, is a real find for the naturalist," the Russian physiologist Ivan Sechenov wrote in 1863 in his book *Reflexes of the Brain.* "He has seen so many diverse and intricate machines—from the simple screw to the complex mechanisms which to an ever-increasing degree replace manual labour; he has meditated so much on these machines that, if you confront him with a new machine without letting him see its interior but showing him only the beginning and the end of its work, he will form a more or less correct idea both of the design of the machine and of its operation."

This is indeed the case, and the brain is just such a closed machine, a mysterious "black box" as the cybernetician would call it. All we can do is trace nerve tracts leading in and out of it. We can detect the presence of incoming and outgoing signals. But we can only conjecture what is going on inside. That, at least, was the state of affairs until very recently. That is why it is important to gain an idea of the principles of cerebral activity on the basis of "input-output" signals. For this purpose a machine analogue of some kind is inevitable. It is not surprising that nineteenth-century workers sought analogues of our wonderful living machine in familiar technical hardware.

The vital functions of the organism make up an endless chain of reactions following the simple pattern of stimulus-response, or as they say today, input-output. Each such cycle need not correspond to the mechanical pressing of a specific

button. One could envisage it in the form of a switching device which connects the relevant elemental units. Something like a telephone exchange, where every subscriber is connected with the whole town but at any specific moment he can contact only one other subscriber. You want to make an appointment with a friend and dial his number. You can ring up every number in the telephone directory. You can contact tens of thousands of telephone subscribers at will. Our brain may well resemble a telephone exchange, with countless neurons acting as automatic switching units.

"Some such automatic switching device probably operates in the brain," Pavlov wrote. "It connects the brain area responsible, say, for vision with the area responsible for digestion. The result is that the dog salivates when a light is turned on."

This comparison of the central nervous system with a telephone exchange can be found in many of the great physiologist's works. For a long time this was regarded as a very comprehensive analogue, and the simplest cerebral activity and the most complex aspects of human behaviour appeared to fit into the telephone-exchange scheme.

Take motion. A burnt child pulls its hand away automatically, subconsciously. It is an inherent property of the nervous system, a mechanism which invariably responds to stimulation, an *unconditioned reflex.* Other responses develop as one's range of experience widens. The manner in which they are carried out depends on the conditions in which a person may find himself. These are acquired or *conditioned reflexes.* It is the kind of reflex that comes into play when, for example,

a thirsty man reaches for a glass of water. This is a deliberate motion which is carried out only when the organism needs water. When this happens the brain's thirst centre "rings up" its neighbours and asks for help. A system of automatic switches connects it with the motor area, which issues the necessary commands, and the hand reaches out for the glass of water.

Or a man sees a car driving towards him down the street. The signal from the eye comes to the visual centre, which makes a connection with the motor area. The latter issues a command to the legs and the man steps aside. It does look very much like a telephone exchange.

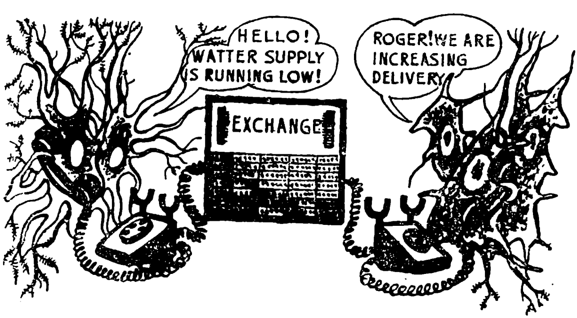
But the closer the physiologists investigated its operation the less sure they became, especially when they turned from "fragmentary movements", as Professor Bernstein calls them, such as pulling a hand away from a source of pain, to purposeful movements associated with work or sport. Many puzzling questions arose.

The brain receives information concerning the state of the muscles, the angles made by various joints, etc., at a given moment. But how does it know what should be adjusted and to what extent for, say, a volleyball player to jump just high enough to reach the ball as it passes over the net or for a worker to put the finishing touches to a newly machined part? For the brain's information relates only to the actual state of affairs. It is left to the brain to decide what is still to be done. Neither do the commands it issues give any indication as to the purpose of a movement. They just tell the various muscles what to do. Yet one senses the existence of an elaborate programme behind every deliberate motion.

"When we physiologists got that far in our rea-

soning," Professor Bernstein says, "it became apparent that the job was much too difficult for a 'telephone exchange' to handle. An exchange connects subscribers without thinking. The brain must constantly appraise the situation, decide on the action required and the motor activity best suited to achieve it. The brain is faced with specific motor problems and it must plan how to handle them or, as we now say, it must programme its work. The action itself is the easiest part of the job. Yet before, when workers first began to study the dynamics of the human body, they thought it was the brain's most difficult task."

"Programming" and "data processing" are technical terms without which it would be impossible to describe a cybernetic system. Today physiologists, too, use them, but what battles the pioneers of this usage had to withstand! Looking back, one finds it difficult to comprehend the reason for the initial opposition to the "cybernetization" of physiology. After all, no one was disturbed by the "vulgar" comparison of the brain with a telephone exchange. "How inappropriate it seems at first glance to compare man, with all his ideals, aspirations and complex motions,



with a machine," Pavlov wrote. "But is it really so inappropriate?... For man is undoubtedly a system (or machine, to put it simply)... obeying the inevitable uniform laws of nature; but he is a system which, from the point of view of modern science, is unique in the extent to which self-regulation is utilized."

In Pavlov's time a telephone exchange was the closest technical analogue to the work of the brain. In our day the horizons of scientific outlook have expanded, and modern cybernetic machines can be compared quite appropriately with the brain. Such machines process and analyse information received from sensors and come out with an answer: what, say, must be done to maintain the temperature of steam in a boiler when its pressure is reduced by two atmospheres.

Information about conditions on the periphery of the body streams continuously into the brain, which must analyse it and decide how to act. A major share of the information is supplied by the eyes; optic nerve tracts transmit some thirty times more data than the acoustic tracts. The brain's responses are very laconic. It is estimated that the volume of incoming information is about seven times greater than the output control signals.

A cybernetic machine contains a great number of electron tubes. The operation of a tube is ridiculously simple: it is either "on" and transmits current or it is "off", and doesn't. The "on" state can be used to denote "zero", and the closed state, "one", or vice versa. The basic machine operations can thus be reduced to computations, which is why these machines are usually called computing machines, or just computers.

Thus, the machine answers either "yes" or "no" to a sequence of questions. On the basis of

the answers it arrives, step by step, at the correct solution.

Could the work of the brain be based on the same principle? For in the brain one observes a continuous flicker of action potentials, and neurons are the living organism's "electron tubes" that are either open (on) or closed (off) to nerve impulses.

Neurons, it should be noted, conform to the "all-or-none" principle well-known to physiologists. That is, they are either at rest, when a stimulus is below the excitation, or "firing", threshold, or they fire, when the stimulus is above that threshold. On the state of the neuron depends the path of a nerve impulse, and hence also the pattern of the neural communication circuit and the nerve centres that enter into it.

A population of neurons thus appears to operate along computer principles, and before the brain can decide on the nature and destination of specific control signals it must go through a series of calculations. This was demonstrated in a study of the way in which the brain controls the dilation and contraction of the pupil of the eye. The apparently simple, subconscious action requires a substantial amount of preliminary computation. Information concerning the illumination of a room or the object under inspection is transmitted to the brain, which determines the aperture best suited for the specific "seeing" task. It compares the computed value with the actual aperture and determines the amount by which it must be altered. Only then is the command issued to the relevant muscles. The computation is so precise that the aperture may change to within a fraction of a millimetre. This is a routine computation,

one of the kind the brain is continuously engaged in.

Inasmuch as the effects of a command may vary depending on circumstances, the brain must solve not simple arithmetical problems but whole differential equations for no greater purpose than to control simple, subconscious motions of the arms or legs. This should not be taken to mean, of course, that our nervous system is inherently familiar with higher mathematics. Knowledge of mathematics is completely irrelevant, and the brain's ability to compute is no indication of its mathematical talents. In fact, all animal brains are computers. Zoologists know that if an egg is surreptitiously removed from a bird's nest the bird is apt to get agitated, which means that it "counts" the eggs.

Many of the human brain's "computations" serve no useful purpose whatsoever. It was once observed that the workers of a shop in which mercury-vapour lamps were installed low over the workbenches tended to tire faster than other workers doing the same job. A careful study revealed that this was due to the incessant imperceptible flicker of the lamps; the brain, the physiologists found, kept "counting" the flickers, and this, naturally, caused it to tire faster.

To summarize, the known facts of cerebral activity appear to indicate that the living brain is a computer of sorts.

Step Search

The idea was questioned even before it had had time to take root, and it was the physiologists who questioned it. Their refusal to treat the brain

as a computing machine was not altogether unfounded. When experts studied some problems in motor and other activity which the brain must continuously deal with they came to the conclusion that the nervous system could never cope with them if it had to "compute" them. A fairly simple action was analysed: the motions a person has to go through in pocketing a ball in a game of billiards. The mathematical operations needed to compute the action, scientists found, are so great that the brain could never go through them in the brief space of time a billiard player has to deliberate on how to hit the ball. Besides, many motions simply defy mathematical treatment and cannot be programmed in detail even when they are of an iterative nature. The muscular mechanisms responsible for our motions are much too complex and the circumstances in which the organism must function are much too variable for this. It is impossible to provide in advance for every contingency. Moreover, there are usually a number of ways of building up the same movement.

This suggests a kind of experimental activity of the nervous system which selects out of a number of possible combinations of muscular activity those which achieve a set goal most economically and in reasonable time. That appears to be the function of the brain: it continuously seeks the most efficient assignment of duties to different muscles. In other words, it tests various control patterns and chooses the best.

A similar situation is found in technology when it is necessary to control complex systems with many degrees of freedom. Attempts to solve such problems with the classical apparatus of mathematics are often unsuccessful. As the

cybernéticians say in such cases, the problem is not suitable for programming.

Two Soviet mathematicians, Israel Gelfand and Mikhail Tseitlin, undertook to find a way out of the difficulty. Their idea was to build a machine which would automatically seek the required values. Such automatic search can be carried out in different ways.

First, there is "random" search, which involves all the quantities entering into the specific problem. The search continues until the required quantity turns up. The process of scanning all available numbers can be envisaged as an endless series of trials and errors in which the machine "memorizes" its errors so as not to repeat them. The procedure is of a purely statistical nature, and no single trial and error offers any clue as to where to look for the required number. Conventional cybernetic machines are based essentially on the trial-and-error method of operation, in which the correct answer is found by rapidly scanning hundreds and thousands of numbers, words, notes or any other relevant elements.

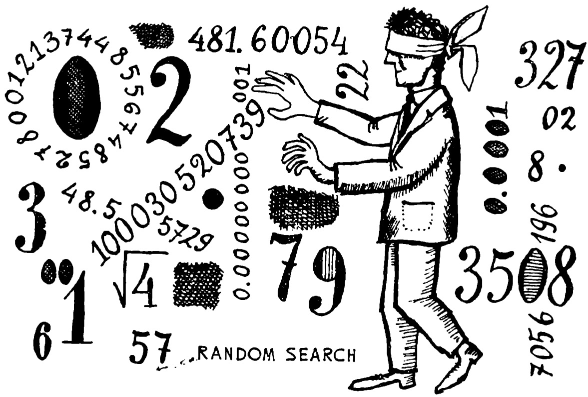
In its simpler functions the nervous system probably acts along similar lines. It scans different combinations of muscular flexions and joint angles at random until it hits on the ones which yield the required result. The brain does not waste its time memorizing how good or bad the scanned combinations are. In fact, it is too busy flipping through the successive sets of values.

Scientists say that the cost of this kind of search is too high. Nevertheless, the organism resorts to it when there is no time to carry out a more systematic search. This is the case of

simple reflex motions, such as pulling a hand away from a hot iron or starting when a firecracker explodes behind your back. This is probably how solutions for most defensive reflexes are found.

Better results can be achieved by the more complex method of "local" search. The brain begins by selecting a set of muscular flexions and seeks perfection in neighbouring sets. This is something like tuning the wireless. You find the programme you want and turn the knob back and forth until the sound comes through clearly. In this mode of search each trial is analysed and the results of the analysis serve as the initial data for the next trial. The search proceeds in a chosen direction and the quality of the requisite motion gradually improves. The perfection takes place in the course of the action and no time is lost. More, the brain has time to memorize the intermediary tentative results of the action. Local search is probably resorted to for relatively simple actions in mildly difficult circumstances.

It is obviously a more efficient method than random search. But what happens if the selected set of muscular flexions is not effective enough and there is nothing better in the neighbourhood of the selected set? In this case the various quantities must first be classified according to their importance into primary and secondary. For although many muscles and joints take part in any movement their degree of participation varies. The work done by some muscles and the change in angle of some joints may be small but they may have a considerable effect on achieving the goal. For example, you wish to touch the tip of your nose with your forefinger. A very small



deviation in the shoulder or elbow joint can take your finger wide off the mark; the position of the wrist is not so important and can be easily adjusted. Having determined the muscles and joints which are mainly involved in a required motion it is possible to look for the best set of elementary movements to carry it out. How is this done?

A combination of muscular flexions is first chosen at random, as in the case of random search. Then a local adjustment is effected, as in local search, to find the best variant in the neighbourhood of the initial set of values. The process is then repeated for a new set of randomly chosen values at some distance from the initial ones. Then comes the most important stage: comparison of both adjusted variants and elimination of the less suitable set. A third set is now chosen—not at random any more but on the basis of the preliminary search. This is repeated many times: a random selection of the first available combina-

tion of values, followed by local adjustment, then a big jump and another local search, followed by another big jump depending on the results obtained, and so on.

This mode of search has been called "step" search, and it will be observed that it incorporates the aforementioned simpler modes. The secondary values are determined in the course of local search, the primary ones, which substantially affect the action, in the course of the "steps".

If the "steps" are correctly chosen, the degree of local search diminishes. More attention can be given to the steps, the search proceeds faster and "costs" less. If eight or ten quantities are involved the cost of the search drops to fractions of that of the two simpler methods.

Thus the speed and success of the search depends on the quality of the steps. A judicious choice of steps takes a traveller over low hills and around high mountains. A decision to end the local search and make another step requires an appraisal of the situation, which takes time. The more complex modes of search involve analyses of events separated in time. They are comparatively slow but they yield better results. In the simpler modes each stage is faster because the events to be evaluated are much closer in time.

Does this mean that if we monitor the internal processes and record their rhythm we can determine the method used to locate the required quantity? Yes, the mathematicians say. Knowing the frequency of the electric pulses within the electron tubes of such a self-organizing automaton it is possible to determine the manner by which the solution is reached.

Guessing Game

The idea that in the more complex cases the brain prefers search to computation occurred to physiologists when they got acquainted with Gelfand and Tseitlin's mathematical theory. They recalled that they had observed something similar before. Thus, Professor Victor Gurfinkel, a member of the team which developed the artificial hand controlled by brainwaves, spent many years studying the way in which the body keeps motionless. It must be said that standing at attention is not such a simple task as it may seem. The brain must continuously control the spine and the muscles of the legs. Almost all the muscles of the body take part in this apparently simple action, which makes it a typical case of control of a complex system with dozens of degrees of freedom. At the same time it is very convenient for observation and study as there is no need to look after every single muscle involved. It is sufficient to observe the position of the body's centre of gravity, the shifting of which accounts for the inclination of the body.

Professor Gurfinkel made a thorough study of the position of the centre of gravity of a standing man. The results were surprising. Although the man stood quite still his centre of gravity was continuously oscillating. Moreover, the oscillations were found to be fairly constant for different people, not depending on a person's height or shoe size (i. e., on the supporting area), or even on his weight. The latter seemed especially strange. Professor Gurfinkel carried out a series of special control tests in which the weight of his subject was varied by means of a loading device. The results were the same. The

frequency at which the centre of gravity oscillated changed only when a person was given large doses of drugs having an inhibitory effect on the nervous system. It thus appears that staying still is also a form of motion. Though invisible to the eye it is nevertheless complex. The apparent motionlessness conceals the continuous activity of the brain. Every instant it must adjust muscular tensions in the best possible manner.

How is this achieved? Obviously not by computing the required muscular forces and angles, for standing upright presents as complex a problem as pocketing a billiard ball. And we already know that such a calculation would end long after the motion began. The conclusion is that the brain determines the required values empirically.

Is it not, then, possible to guess the manner in which it searches? This is what workers of the laboratory of biological cybernetics, where Gurfinkel and Tseitlin work, are trying to do.

I visited the Institute of Biophysics just when the laboratory workers were embarking on a new series of experiments designed to find out how man and machines "think".

A record of the oscillations of the body's centre of gravity provides a graphic picture of the work of the brain. And we know that the rhythm of such a system offers a clue to its mode of operation. Three modes of oscillation of the body's centre of gravity were discovered: small oscillations of 8-10 per second, larger and slower oscillations with a period of about one second, and finally, a slow swaying motion with a period of thirty to sixty seconds. All three frequencies are well defined and mutually independent.

"It is as if there were three different mechanisms at work," Professor Gurfinkel said. "They probably correspond to three different control levels in the multistoreyed arrangement of the central nervous system."

"Now," he went on, "observe the shape of the curve recording all three types of oscillation. What does it remind you of?"

I had never seen the diagram before, yet it seemed vaguely familiar: a rapid upsweep, a series of downward mincing zigzags, another upsweep, and again a series of rapid oscillations. It looked like a diagram of step search, I thought.

"Exactly," Professor Gurfinkel confirmed, gazing meditatively at the chart. "It strikes the eye at once. We have assumed that the rapid rises of the curve correspond to step search while the faster and smaller oscillations correspond to local search for the optimum equilibrium point. We are now trying to verify these ideas."

While the scientists seek to confirm their hypotheses, let us see what conclusions can be drawn from them. First of all, they suggest that the brain is not a plain calculating machine. It is probably more like the cybernetic devices technically known as analogue computers. Such machines do not require a programme to be translated into digital language and they are not used to calculate, say, the number of bricks to be delivered at a construction site every day to complete a building on schedule. An analogue computer is fed, for example, the temperature inside a blast furnace, the air pressure and the composition of the charge, its task being to state the optimum operating conditions of the furnace. Or it is fed the speed of an aircraft and the

strength of the headwind and must determine the best flight conditions.

In such cases the machine does not "calculate". It deals not with numbers but with physical quantities. Not the actual temperature or pressure, of course, but with their "analogues". Temperature, for instance, may be denoted by the current in amperes generated by a thermoelectric measuring device, and pressure by voltage. The machine constitutes a kind of electronic analogue of the processes going on in the blast furnace or in the earth's atmosphere. It selects the components participating in the "game" one by one and analyses their effects, continuing until it chances on the optimum variant. Then it reports: for the blast furnace to operate economically and to full capacity temperature must be maintained at so-and-so, pressure at so-and-so, etc.

Sometimes the machine is made to look after the controlled variables itself. In this case it continuously constructs new analogues, depending on the changing temperature or pressure. It introduces the necessary corrections in the processes, thus acting as a control unit.

Our brain operates in a somewhat similar manner. It "mentally" constructs an analogue of the future motion, utilizing, of course, its incomparably greater capabilities. The different storeys of the body control system operate in different ways. The lower levels, which are similar in operation to simple automatic governors, most probably seek the required sets of muscular tensions at random. The more complex regulators in the level above are apparently capable of appraising the chosen values to some extent and improving them by local search. The topmost

levels of the brain carry out complex analyses in which they compare widely separated quantities and detect general tendencies in their fluctuations. This is done empirically, without computation. That our brain is an analogue system which employs "step search" is a discovery of tremendous importance and it is finding increasing confirmation. We shall return to step search later on. Meanwhile let us see what happens next.

It is not sufficient for the cerebral cortex to solve the motor problem, that is, to determine by experiment what muscles should contract at what precise moment for a person to reach out and pick a glass of water off the table. The brain must also anticipate what the action will lead to. In other words, it must look ahead and develop an analogue of the future as well as of the present. This, of course, does not mean that our brain has to be clairvoyant! Read a few sentences out loud. Do you notice how your eyes run ahead of the syllables you are actually pronouncing? The brain always looks a little ahead in order to assess what it has to do the following moment, what muscles of the face and larynx will have to be activated in order to pronounce "ay" or "oo".

Or try and recite a poem to yourself by heart. You will observe something like two parallel texts running along in your mind, the one that you are reciting and, in the background and slightly ahead, the same text recited by a sort of internal prompter.

The brain does more than just gather pertinent information, analyse it and draw up a programme of work. It anticipates the possible results of its actions. This, of course, can be done only approximately, by judging the probable outcome of

this or that process. The error is the greater the farther ahead the anticipation.

The ability to look ahead, to anticipate the results of deliberate actions, is an essential quality of living self-regulating systems, whether human or animal.

At Moscow University I once saw an interesting experiment staged by Leonid Krushinsky.

A trough with food travels slowly along a toy railway track. Walking after it and pecking at the food is a common crow. The trough disappears into a tunnel. The crow is nonplussed. It sticks its head into the narrow opening in the hope of following the trough. Then, as if suddenly realizing the futility of this course of action, it runs round to the other end of the tunnel. Beak open, wings spread, it is in a great hurry. At the other end it stops and waits impatiently for the trough to emerge. It peers into the tunnel and does not even attempt to look elsewhere.

The impression is that the crow has mentally "extrapolated" the path of the trough and is quite confident that the food will duly arrive.

The fact of the matter is that the crow has actually solved a kinematic problem with several unknown quantities. For the trough was out of sight for a certain time and the crow had to anticipate where it could be expected to re-emerge at the speed and in the direction it was travelling. Mathematically speaking, it had to find the law of motion and use it to trace the trough's path through space in the immediate future.

Obviously, the crow did all this quite unconsciously. We could say that it was not the bird but its nervous system that performed the task. And, as you see, it was quite successful. No

special mental abilities were needed. The success or otherwise of such actions depends solely on the degree of perfection of the animal's nervous system. Pigeons and ducks, for example, are practically incapable of anticipation. Crows, and even more so cats and dogs, possess the ability of anticipation. In man it has reached the highest level.

The idea of a "prognosticator" of sorts in the brain would appear to have originated with engineers or mathematicians. "It is up to the physiologists," one cybernetician wrote, "to prove the existence of such 'prediction networks' in living organisms."

What do physiologists studying man's central nervous system think on this score?

Cybernetic Training

Professor Pyotr Anokhin, veteran Soviet physiologist, pupil and collaborator of Ivan Pavlov, is a pioneer in what Academician Berg calls neurocybernetics. He has devoted forty years of his life to the study of the physiology of the nervous system and probably knows more about the living brain than any other person. Anokhin is not an ivory tower scientist. He took part in the Civil War which followed the 1917 Socialist Revolution in Russia, and in the last World War he worked in army hospitals and performed many remarkable operations on wounds involving lesion of the nervous system. A brilliant experimenter, Anokhin is also a talented teacher; he has been lecturing at Moscow University for many years. He is the acclaimed head of the Soviet school of physiologists, and hundreds of his pupils

work in laboratories all over the country. At seventy Professor Anokhin has great confidence in youth. He readily assigns important experiments to young people. His collaborators range from Dr. Nina Shumilina, who worked with him in Pavlov's time, to Vladimir Polyantsev, a young scientist who looks hardly older than the students he teaches. Besides lecturing at the university, Professor Anokhin works at the Institute of Physiology and the Burdenko Institute of Neurosurgery, and he is an executive member of the International Union of Physiologists.

"I'll hardly get through to such a busy man," I thought as I dialled his telephone number for the first time. "Some pert secretary will probably inform me that the professor is busy and hang up."

So when a masculine voice answered the phone I was rather taken aback. "Professor Anokhin?" I asked, hardly believing my ears. This was my first pleasant surprise. It turned out that he had no reception room no secretary, not even a desk or telephone extension for her. The desks and tables in Professor Anokhin's office were littered with photographs, galley proofs, booklets and books in many languages. Book shelves lined the walls. A veritable library. But the man who turned to greet me looked hardly a bookworm. He was big, hearty, unexpectedly curly-haired—and active. He kept walking back and forth, not even sitting down to go through various papers. He would finish one, toss it aside and pick up another without halting for one moment. The telephone rang and someone reminded him of a forthcoming meeting of the physiologists' society, where he is chairman. Institute workers passed in and out of the office in an endless stream,

reporting on work done and bringing in papers and charts. I felt as if I were in a kind of headquarters of physiological operations preparing for a campaign.

"I've just arrived," Anokhin explained apologetically. "That's why there are so many callers."

However, when I saw how readily Professor Anokhin let the whirlpool of affairs draw him in I felt that it was not a case of an emergency rush job. In fact, there was no rush, just the hustle and bustle of routine work. It was like a lull before a storm, when people sense the coming of great events. Today they are happening somewhere nearby; tomorrow they will be here.

It is apparently characteristic of all eminent scientists that even on the most routine days they act as if they were on the front line of discovery. Hence the effervescent bustle of life, the youthful ardour, the ability to make instantaneously the only correct decision.

"But I'm afraid you'll be late for the experiment," Anokhin suddenly remarked. "I asked you to come today so that you could attend a cybernetic experiment. You had better go to the laboratory."

I was shown to the laboratory where Vladimir Polyantsev, Anokhin's pupil and associate, was busy with several students preparing a rabbit for the experiment. The animal lay on its back, its paws strapped down to the table, its head drawn back. The skin on its neck was cut and drawn apart to expose the gullet. Along both sides of the gullet there ran two shiny white threads of nerve fibre. A thin wire was clamped to one of them.

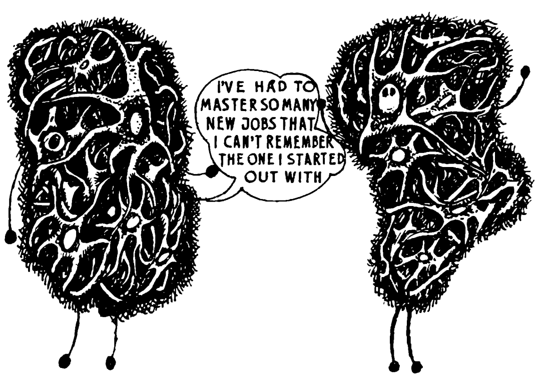
"We are listening in to the nerve," Polyantsev explained. The table with the rabbit was inside

a large wire cage. A long wire dangled in Polyantsev's way and he looked for a place to fasten it to. Finally he hooked it to the top of the cage. I made a move to enter the cage, but Polyantsev stopped me.

"Out of bounds," he said. "You'll have all these wires wrapped around you in no time."

The cage door slammed shut, concealing Polyantsev in his white smock and doctor's cap and the rabbit. The room looked more like a physical than a physiological laboratory. On the tables stood several oscilloscopes, their screens glowing like green traffic lights. Long strips of paper covered with curves repeating the dancing patterns on the glowing screens lay on a table. A maze of varicoloured wires criss-crossed the room from the rabbit cage to the oscilloscopes and to a mysterious gurgling box next to me. All of a sudden the box clicked and a red light lit up on its front wall.

"Well, here we go," Polyantsev said, stepping out of the cage. He walked up to an oscilloscope



with bright zigzags rushing crazily across the screen. "Our experiment today is to demonstrate how the respiration centre can be retrained." He twirled some knobs. "We pick up nerve pulses in the respiration centre and view them on this screen." He looked at me, quite evidently annoyed at having to waste his time explaining such simple things. He went on hastily to get it over with: "The rabbit is anesthetized. This thing next to you is a lung machine. The rabbit's respiratory rate can be artificially regulated by increasing or reducing the flow of air through this valve. We can also make the rabbit itself choose the respiration rate it requires."

Polyantsev gradually warmed up to the subject, his white doctor's cap slipped to the back of his head and a lock of blond hair kept falling into his eyes. He waved his hands and moved from the oscilloscope to the lung machine and back again.

"We can thus see for ourselves how the respiration nerve centre works. To show it more clearly we place the organism in extreme conditions. For instance, the diaphragm stops working. The respiration centre sends one command after another, but it doesn't contract. What happens then? Look here."

Polyantsev closed the valve supplying air to the rabbit's lungs. The machine stopped gurgling.

"The rabbit will begin to suffocate." The young researcher screwed up his eyes. "The organism will look for a way out. The respiratory muscles do not contract, so other muscles will be tried. The respiration centre in the brain sends out an SOS signal, as it were."

The rabbit's legs twitched and a shudder passed through its body.

"See?" Polyantsev said. "It doesn't want to die, it fights for its life. Now we connect the lung machine to the leg muscles. Their contraction opens up a flow of air to the lungs. The brain immediately grasps this last straw of salvation and starts regulating the contraction to ensure an adequate supply of air." Polyantsev turned to me. "Observe how it controls the lung machine with its leg."

Sure anough, the rabbit was jerking its leg rhythmically and the lung machine came to life. It clicked and gurgled in unison with the moving leg: slowly at first—one, two—then faster: one-two, one-two, one-two.

"He's breathing, breathing with his leg!" Polyantsev shouted joyfully. He rushed to the oscilloscope, peered at the screen, adjusted something and swore under his breath when interference appeared. He lost all interest in me, answered my questions absent-mindedly and kept looking up at the ceiling as if questioning it about what we were speaking. Even as he grasped the thread of the interview his eyes would turn back to the oscilloscope screen and he would mutter or hum under his breath, depending on how the rabbit behaved. He would come back with a start: "So you were asking...."

I realized that the interview was as good as over and unobtrusively took my leave—only to come again and again, until I gained a clear idea of the purpose and the details of this remarkable experiment in "retraining" nerve centres. An experiment, first staged by Pyotr Anokhin thirty years ago, which has since become a classical method in brain research.

King For a Day

I don't know how much young Anokhin was like his pupils of today in other respects, but I'm quite sure that they had at least one thing in common and that he too used to spend days and nights on end in his laboratory, forgetting about food or sleep when anything went wrong—and even more so when an experiment was going well. Had he not been such an enthusiast we should never have known him as the great scientist he is. In those days his laboratory had nothing like the electronic hardware it has today, and the laboratory itself was not in Moscow but in Gorky.

Anokhin took a dog and switched over the nerves leading to the respiration and tactile (touch) centres. As a result the relevant signals were readdressed to the wrong nerve centres. Some unusual responses resulted: he touched the dog's leg and it coughed, he stroke its back and it retched, he didn't touch it at all and it waved a paw in unison with its breathing. But after all, there was nothing strange in this since stimulations carried by tactile nerve tracts were conducted to the respiration centre or to the area of the brain responsible for stomach contraction.

Then gradually the dog's behaviour returned to normal. This meant that the nerve centres had "retrained" and learned to perform new tasks needed for the organism to function normally. But this was possible if and only if the nerve centres concerned were informed that their commands were misdirected. We know today that this is the case and that there exists an elaborate system of information feedback in the organism. To young Anokhin the idea of feedback control was a revelation.

His discovery came at about the same time when Nikolai Bernstein was embarking on his investigations. Actually, they both came to the same conclusions on the basis of different observations: Bernstein by analysing the motor activity of human beings, Anokhin through his experiments in "retraining" animal nerve centres.

This, in effect, marked the beginning of cybernetics. Feedback in machines had been known long before that. Now a similar control system had been discovered in living creatures. It had developed and evolved as an essential feature of living systems. Feedback, which conveys information about the results of an action to a control centre, enables animals to adapt themselves to an eternally changing environment, to survive, in other words.

The obvious conclusion appears to be that closed-loop feedback is a universal principle of action of each and every cybernetic system. Unfortunately, the conclusion was drawn many years after the original discoveries, and the birth of cybernetics is consequently officially considered to be 1948.

The deeper physiologists penetrated into the secrets of the structure and functioning of living organisms the less similarity they found in common between living and mechanical control systems. Take the case of feedback.

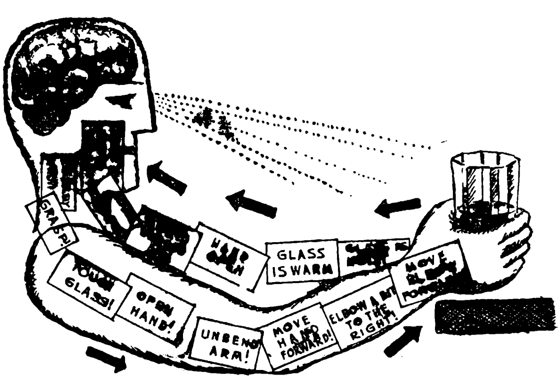
The necessity of monitoring information about the results of an action was clearly demonstrated in the experiments on the "retraining" of nerve centres. The central nervous system is informed by sense organs of the results of an action and is able to judge its effects. Without this the organism would never be able to revert to its normal behaviour, and in the case of Anokhin's

experiment the dog would always behave as absurdly as immediately after the operation.

Despite its wide variety the information fed back to the brain can be classified into several more or less distinct types according to the role it plays in the animal's behaviour.

You reach for a glass of water. The motion is accompanied by a continuous stream of messages from the muscles involved which keep the brain informed that at every given instant things are proceeding according to plan. The tensions in the arm are just right, the relevant muscles have duly flexed, the hand is correctly positioned to grasp the glass, etc. This "organizing" information, as it may be called, is very important. No action can be carried out without it.

"Unfortunately," Professor Anokhin says, "we frequently see feedback in organisms and machines compared only on the basis of this type of information. Yet, by its very nature, this does not tell the nervous system of the results of an action; the hand's position and the signals from the corresponding receptors offer no indication



as to whether the hand has grasped a glass or a cup."

Nevertheless, the feel of the glass, temperature stimuli, the weight of the glass and water, and finally, visual observation, combine to tell the nervous system that the goal has been achieved. Thus, in addition to current information, the brain receives complex messages on the results of an action. They are monitored back, not when the whole motion is completed, but at each successive stage in the movement. The nervous system does not go over to the next stage until it is informed that the preceding intermediate action has been completed. This is seen in the following experiment.

A common inhabitant of ponds and lakes is the water scorpion, a rather primitive bug which forages for food with as little effort as possible, just by waiting for some small insect to come within reach. Then it shoots out a foreleg, grasps its prey and dispatches it into its mouth. The action is completely automatic. If the scorpion's mouth is removed, leaving the eyes and cerebral ganglion (which is an insect's equivalent of a brain) intact, it goes through the same process: it grasps its prey, brings it up to where its mouth should be—and petrifies, as it were. With no mouth to open and take the food the scorpion will remain in the posture indefinitely.

The experiment is varied by cutting off the tip of the insect's leg with which it grasps its prey. In this case it will reach out for a morsel, without bringing the foreleg up to its mouth.

In the first case, evidently, the foreleg clutching the prey freezes into immobility because the nerve centre receives no message from the jaw muscles, which it needs to complete the action. In the

second case the water scorpion does not complete the motion of its foreleg because its nerve centre has received no message that the prey has been caught. In either case no useful purpose is served by continuing the action.

Professor Anokhin cites this example in one of his works on neurocybernetics to stress the importance of information feedback. At each stage of a complex motion a go-ahead signal must be supplied to the central nervous system before it can order the motion to be continued. This is the second type of information, which Anokhin calls endorsing or authorizing information.

The brain must be able to distinguish this especially important information, it must know whether conditions allow the previously prescribed programme of action to be pursued further. Above all, it must be able to assess whether the performance has been as intended or whether something has gone wrong. This the organism does without difficulty. If you miss the glass of water and grasp a book that was lying next to it you notice your mistake at once. Before you know what's what your hand pulls back to start the motion anew. The brain registers the mistake before you are conscious of it. How does this happen?

"It appears," Professor Anokhin says, "that before carrying out an action the brain sets up a mechanism for evaluating its anticipated result, against which it matches the actual result."

The control mechanism, which Anokhin calls the "action acceptor", does more than just mechanically compare the programme of action and its fulfilment. It reports to the brain that all is going well, and the brain acts on this information. If for some reason the motion does not achieve

the desired result the action acceptor takes over control and sets matters right. The mechanism exercises control over reflexes, guiding them in the right direction to achieve the necessary result. Information from our sense organs and muscles converges at the action acceptor. It compares data coming in from body receptors with the required values and determines what must be adjusted for the action to achieve its purpose.

We find the object we are looking for. We see a mistake in our actions and rectify it. Our behaviour is conclusive, it does not degenerate into a series of isolated actions. It is dovetailed to circumstances with a high degree of precision and it never "idles". This is because the usefulness of every action is checked by a special "judgement" mechanism. The need for such a rationalizing mechanism developed in the course of evolution. Any reaction of a living organism may display a variety of shades of behaviour. The important thing is to select those which facilitate survival and adaptation to the environment. In lower animals the usefulness of a response is verified by means of a feedback system connecting the control centres and effectors. In higher animals, and especially in man, actions are so complex and diversified that a special mechanism—the action acceptor—is needed to deal with the mass of information coming up the numerous feedback pathways. As it must anticipate the outcome of an action we can assume that this is the prediction mechanism about which so much has lately been said.

The most interesting point, though, is that no evidence of its material existence has so far been found in the brain. What is this mysterious action acceptor? An as yet undiscovered aggregate of

specific neurons in the brain? Or are its functions carried out by various groups of cells as the need arises?

The latter notion appears to be the most plausible one. For the nature of prediction must necessarily vary in different circumstances. Thus any company of cells may be elected "king for a day", with its predictions holding only for specific cases. When the action is completed its reign ends and a new predictor takes over.

Discovery of the "action acceptor", or prediction mechanism, dealt the first blow at the concept of the brain as an ordinary cybernetic system hardly differing from its "intelligent" mechanical counterparts. But there were more surprises in store.

Terra Incognita

They were blank spots on the charts of the brain. These areas in the frontal and temporal lobes did not respond to stimuli of any kind. Application of live electrodes caused no sensations of flashing lights, rumbling sounds or creeping skin in test subjects, as was the case when visual, acoustic or tactile centres were stimulated. Then one day the Canadian researcher W. G. Penfield applied electrodes carrying a very weak current to a man's temples. The effect was as though sound and visual recordings of old memories were being played back in his head. Scenes, sounds, thoughts and emotions of many years ago came to life in vivid detail. The visions disappeared as soon as the electrodes were removed or the current switched off.

Professor Penfield describes many interesting experiments. When an electrode was applied to

the temple of one subject he said that he heard a piano playing. When the stimulus was repeated he heard a voice singing and even knew the tune. The stimulus was applied again, and the subject remarked that it was a song from an opera he had once heard. When the electrode was moved four centimetres closer to the forehead the subject recalled the advertisements he had once seen of a bottle company and a bakery. To make sure that this was not a case of selfsuggestion Penfield told the man that he was switching on the current but actually did not. When asked what he now saw the subject said, "Nothing".

These observations confirm that recollections appear spontaneously and are due to stimulation of the temporal lobes of the brain. In some cases stimulation caused such vivid hallucinations that people were convinced that they were actually taking place. One woman, for example, repeatedly heard the same song when an electrode was applied to the same point on the temporal lobe. It stopped when the current was switched off and picked up from where it had left off when the current resumed. At Professor Penfield's request she hummed the tune as if she were following an invisible orchestra. In fact, she was convinced that she had been following a phonograph playing in the laboratory, and nothing could dissuade her.

The hallucinations always referred to some past experience, often apparently quite forgotten. One patient was so surprised that he exclaimed, "Doctor, I hear my friends laughing!" When asked what he found so remarkable, he said that it was the feeling of himself joining in the laughter with his cousins living in South Africa, although he knew that he was in Canada at the moment.

Different levels of the temporal lobe appear to be responsible for different types of recollections. The upper storeys are responsible for remote events. Even their complete removal does not affect the memorization of recent events. Damage of the lower portions, however, results in loss of memory of recent events, although old memories remain and can be evoked by the application of an electrode. Does this mean that the temporal lobes are the brain's archive, its memory centres?

No, Professor Penfield says. This would be an oversimplification. Events are actually not "recorded" here, but in other sections of the brain which are closely associated with the temporal lobe. An electric stimulus excites a section of the temporal lobe which transmits the stimulus to the place where memories of the past are stored. The temporal lobes switch on a tape recorder inside our head, as it were. They do not store recollections themselves, they merely dig them out of our memory archives.

What are these "archives" like? We have come to what probably constitutes the greatest difference between the organization of the brain and a cybernetic machine. The human brain does not have a special memory store like an electronic machine. At least, nothing like it has been so far discovered. In fact, as some physiologists say, our knowledge of the nature and location of human memory is not much better than that of the ancient Greeks, who considered the midriff to be the seat of the intellect.

In any case, machine memory devices have nothing in common with cerebral memory. In the animal world, a distinction between "long-

term" and "operational" memory, which, as in computers, would be located in different places, has been found only in the octopus. This animal's operational memory appears to be combined with a "computer unit" in the brain, the long-term store being located in a special lobe made up of small neurons.

In man, each receptor of external stimuli appears to have a local memory store of its own. Our brain memorizes visual, acoustic, tactile or motor sensations separately. This explains why some people remember faces but forget names, others can memorize rows of numbers but learn languages with difficulty, etc. The implication is that various sections of the memory develop differently.

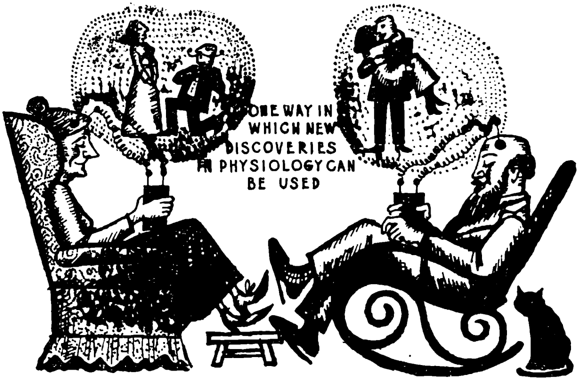
These are things we all know from daily experience. You, for example, easily remember what you read while your friend must repeat a passage out loud or write it down if he wants to remember it. From what we know we can say that in your case your visual memory is better developed, in your friend's it is memory associated with the motor or auditory centre. How these various visual, auditory and other sensations are stored is not, however, known.

Equally vague is our knowledge of the process of memorization. The memory of something seen or heard is evidently a record of the original stimulations of certain nerve centres. The stimulations come to an end, but leave invisible "imprints", which can be subsequently projected in the mind to relive bygone experiences and events and the logical processes linking them. How does the brain store these imprints of bygone nerve connections? This is an intriguing riddle, which continues to baffle both physiologists and

cyberneticians. They can do no more than engage in guesswork on this score.

Some investigators have discovered closed loops of nerve cells and their processes in the brain. Maybe stimuli can circulate round these loops for a long time? The brain could thus keep records of old stimuli that had once excited the nerve centres concerned. On the other hand, the memory of an event may be "smeared out" over millions of nerve cells, with each single imprint representing a small stimulus extending over all of them. Simpler yet, information entering the brain may be "recorded" in neurons as on magnetic tape. Neurons, it was found some years ago, are like little magnets. The brain may well be a kind of storehouse of microrecordings which can be kept as long as required and "played back" at will. I, for one, should like to think that such a perfect system as the brain has adopted such a modern technique, all the more so as it is very convenient. Unnecessary recordings can easily be erased so as not to clutter up the memory with useless items—just what the brain does, in fact.

Man is forgetful, and not without good reason. Old and useless information is gradually erased from our memory, thus making room for new information. In one experiment several persons were asked to memorize an unfamiliar text. Twelve hours later they were found to have forgotten half the memorized information in terms of words and syllables. Possibly 12 hours is the "half-life" of one of man's many memories, i.e., the time in which he forgets half of newly introduced data. Machine memory, on the other hand, holds information practically indefinitely, and very soon it is crammed full. At the same time



the capacity of machine memory is much less than that of the human mind.

I wondered at first how one could speak of the capacity of the human memory store without knowing its location or what it looked like. It is possible, however. Although the exact amount of information that can be stored in the human memory is unknown, an estimate can be made, and it is calculated in precisely the same way as computer storage capacity.

It should be known that when we speak of the information processing and storage capacity of an electronic computer or the human brain we are dealing with an exact mathematical quantity measured in specific units, called "bits", which is a contraction of the words "*bi*nary dig*its*".

Computer storage capacity can be expressed in bits. A conventional electronic calculating machine can take a million bits of information. Special information machines have a storage capacity of a thousand million bits. Is this a lot or a little? Translating these esoteric bits into

lay language, we can say that such a machine is capable of "memorizing" some half a million pages of printed matter, or over two thousand two-hundred-page books.

The brain consists of some 14,000 million nerve cells. Let us assume that "only" 10,000 million of them are capable of receiving information simultaneously. A nerve fibre is known to have an information carrying capacity of 14 bits per second. Taking all such fibres into account, this means that our brain is capable of receiving 140,000 million bits of information in one second. Over an average life span of 60 years this builds up into an astronomical figure. The storage capacity of the human brain turns out to be a million times greater than that of an information-storage machine. How does the brain cope with such an abundance of data, how does it know where to look for the data it needs?

Facts and phenomena, it appears, are memorized not in isolation, but in correlation to one another. Our memory keeps recollection not just of the colour of the sea but also of its coolness, the taste of the salty spray, the sunlight playing on the waves on a hot day, and the silvery path of moonlight stretching away to the horizon at night.

Many facts are memorized in their contextual relationship. In one experiment several people were made to memorize a poem of eighty words. Most of them could say it by heart after eight repetitions. It took 80 repetitions to memorize a meaningless jumble of 80 syllables. The same happens when we recollect things, and one fact often gives rise to a chain of recollections, new facts and events which come to our mind by association.

You meet a man whom you once knew and have seemingly quite forgotten. The feeling of recognition occurs before you can recollect who he is and where you met. As if your mind has received a signal telling it that you know this man. (It probably comes from somewhere in the temporal lobe.) The signal switches on a kind of film projector and memories begin to unfold in your mind. Recognition dawns upon you and you recall his name. The sight of the man and the sound of his voice have acted as stimuli opening up your memory's archives where his role in your past life is registered. The process is a purely subconscious one. Although a moment ago he was an all but forgotten memory, the imprint of the past now stands out in bolder relief. You observe that your old acquaintance has put on weight and there are more crow's feet at the corners of his eyes.

An interesting example of such a retrospective reconstruction of old imprints of the past into a detailed recapitulation of forgotten events of historical importance can be found in the reminiscences of Yelizaveta Drabkina, an old member of the Soviet Communist Party.

"It all began with recollections that haunted me for several years," she writes. "They were vague and fragmentary at first, but gradually they fell into place— — —

"I see a room. No, it is not a room, it is a kind of chamber without doors or windows. One of the walls seems to be swaying back and forth. A dark hole looms where the ceiling ought to be. The scene is illumined by electric light coming from some invisible source. Near the swaying wall stands a gilded armchair upholstered with crimson silk. Seated in the chair is Lenin! He is

very animated. He is speaking about atomic energy— — —

"But no, this must be my imagination. I couldn't have seen Lenin sitting in a gilded armchair. Lenin couldn't have been speaking about atomic energy. It must have been a dream which I later came to recollect as something that had really happened. But, I continue to argue with myself, I never see dreams in colour. My dreams are always 'black and white'.

"Yet I clearly see all shades of red, from a bright crimson to a deep cherry. Now I see that the wavering wall is a dark-red velvet curtain. The armchair is near the curtain. I clearly see its bent, carved and gilded arms and legs. My recollections are already so vivid that I know where it is: behind the scenes of the Bolshoi Theatre during the Eighth Congress of the Soviets.

"Seated in the armchair is Lenin. Several people in similar chairs form a semicircle around him. I strain my memory and recognize my father. Then the tall, wise forehead of I. Skvortsov-Stepanov, the keen, animated features of S. Dvoloitsky, and the spare form of N. Meshcheryakov.

"My memory unfolds and the conversation gathers details which make it appear more and more unlikely. My memory tells me that it dealt with questions of physics, with atomic energy. Albert Einstein was mentioned and someone remarked that he had been accused of bolshevism. I even hear someone speak of space conquest and interplanetary travel....

"I recall that the cause of the conversation was an article in a newspaper or magazine that Lenin was reading and commenting on out loud. To check myself I go to the library and look through old sets of the newspapers *Pravda* and

Izvestia. In vain: they contain nothing of this nature.

"But then I recall that another person was present there, F. Rotstein, a Russian revolutionary, who had spent many years in England. It was he who had brought the article which Lenin was reading. Maybe it was printed in an English newspaper or magazine?

"I search again and, just as I am about to give up the task as hopeless, I find the article in the magazine *Nation* and the place which had caught Lenin's attention."

This story of retrospective recapitulation is most interesting. It seems to confirm the idea, long held by some physiologists, that man never forgets anything. The important thing is to get hold of the right end of a deeply hidden memory chain.

A Brain Within the Brain

A patient sits in the office of the French physiologist Professor Delgado. They are chatting unconcernedly. Unnoticed by the patient, Professor Delgado presses a button and a weak electric current flows to the man's frontal lobe. His features freeze into immobility and he stops short in the middle of a word.

Professor Delgado switches off the current. "What did you feel?" he asks.

"I felt as if my brain went blank," the patient says in some confusion. "As if I were drunk."

This is the effect of stimulating the second of the brain's "terra incognita", the frontal lobe. This portion of the brain is underdeveloped in many animals. In man, however, it is the biggest

area, occupying one-third of the cerebral cortex, as physiologists call the folded surface of the brain. It is also the youngest region of the brain. Two general areas, numbered 6 and 8, can be distinguished, but more and more differences in the detailed structure are steadily being discovered.

Many anatomic connections between the frontal lobes and other parts of the cortex and the inner portions of the brain have been found. This suggests that the frontal lobes are an essential part of the communication system within the brain and possibly play an important role in the most complex types of nervous activity.

Professor Anokhin's laboratory has undertaken a thorough study of the functions of the frontal lobes. The detailed records of experiments on dogs carried out by Dr. Nina Shumilina, Professor Anohkin's associate, present a vivid picture of the day-to-day work and the wonders she and other workers discovered about the "laboratory of thinking".

Seven dogs were chosen for the tests. They had all been trained for different times, varying between several years and several months, to have conditioned reflexes developed in response to a bell, a whistle, the ticking of a metronome, the gurgling of water, a musical note or regular flashes of light. On seeing or hearing the familiar signal each dog goes up to a feeding trough, confident that it will be fed.

The difference from conventional experiments of this kind was that there were two troughs instead of one. A ringing bell, for example, meant food in the right-hand trough, a flashing light, in the left-hand one. In this manner the reflexes could be observed not only in terms of saliva-

tion but also in the animal's movements. The brain has the additional job of choosing between two alternatives, and the investigators can therefore observe more conveniently how it reacts when faced with a choice.

Then one day Dr. Shumilina operated on all the dogs and removed their frontal lobes. She spends hours on end in the dogs' cage. She has no need to read their case histories, for she knows them all, their habits, characters and endurance. Seven different dogs. But now they behave absolutely identically: they stand in strange positions, front legs buckled, heads pressed against the floor. Dr. Shumilina calls the dogs by name and they lift their heads lazily as if they do not recognize her. She tries to feed them, but it is a hard job. The dogs' jaws are locked as if in a spasm. They snap at the food, often nipping the hand that feeds them. They behave in this way for two days after the operation. On the third day the dogs begin to display extreme restlessness. They pace the floor of their cage continuously, breaking into a run at a noise. Their attention is easily distracted. If food is scattered on the floor they pick one piece and pay no attention to the rest of the food, although normally dogs will hunt about diligently until the last morsel is gone.

When the dogs are let out of their cage, they run down the corridor, but on meeting an obstacle they attempt to get through it instead of finding a way around it. At a turning they come to a halt with their heads against the wall. They stand like that for a long time, occasionally shifting their legs.

The dogs appear to have suddenly grown stupid. They cannot even discriminate between

edible and inedible objects and they grasp and attempt to swallow pieces of wood, soap, balls of paper and marbles.

On the third or fourth day after the operation conditioned reflex experiments were resumed. Normally a dog would run into the room, jump onto the bench and offer its jowl for the experimenter to attach the salivation test-tube. Now they ran past the door, they did not recognize familiar places or anyone of the personnel. The dogs had to be led into the room, but even the sight of the familiar surroundings evoked none of the usual responses. They ran about the room, sticking their heads behind the central heating radiator or under the table. It was with difficulty that they were led to their places and strapped to the bench. The first entry in the laboratory journal following the operation read: "After operation, integrated behaviour degenerates into disjointed reactions."

At last everything is ready for the experiment. The familiar signal is given. How will the dogs respond? Will they remember which of the two feeding troughs they must approach? The bell appears to evoke some response, and the dogs wander towards a trough—but only to the one that happens to be closer. And although Dr. Shumilina rattles the other trough as she fills it with meat the dogs stand indifferently at the empty one.

Frontal lobectomy, as the operation is called, thus appears not to have completely destroyed the animals' conditioned reflexes. Stop-gap communication remains between the various parts of the brain. The animals hear, see and feel, although their sensations are distorted and they are unable to discriminate between the

useful and useless impressions entering the brain.

On the second day of the experiments the behaviour of some of the dogs suffered a change: they approached one trough, turned to the other, then back to the first one, as if unable to decide which trough to choose. They had forgotten which one was to be filled with food. Most surprisingly, some of them even resumed this pacing motion after feeding. Several days later, the very sight of the room caused the dogs to turn back and forth. They moved faster and faster, more and more dogs joined in, and they swerved to and fro with the regularity of a pendulum. It was a strange sight indeed. Even when a dog halted for a few moments at a trough its front quarters would swing away as if drawn by a magnet and the dog would continue its swerving.

"The swerving to and fro appears to be a forced, automatic motion," a new entry appeared in the laboratory journal.

When Dr. Shumilina counted the dogs' swaying motions she observed that they followed a definite pattern, the number of turns being more or less related to the number of signals used in the earlier experiments. Six to eight turns, she found, corresponded to a bell or metronome having been switched on more than 2,000 times in the experiments before the frontal lobectomy. A musical note which had been sounded 109 times yielded four or five turns. A weaker stimulus—gurgling of water but reinforced by 493 repetitions—evoked as many turns as the musical tone.

The swerving reaction proved to be remarkably constant. Small wonder that the investigators concentrated their attention on this phenomenon.

"Physiologists call such behaviour 'locomotor restlessness'," Professor Anokhin later wrote. "But does this term tell us anything more than that an animal executes more motor acts than before? Is this sufficient for an understanding of the nature and physiological meaning of the processes responsible for the superficial manifestations of restlessness? An analysis of this phenomenon is essential."

A series of thorough experiments was launched. It was natural to assume that the manifestations of locomotor restlessness—the swerving back and forth between the troughs—were in some way related to the dogs' earlier experiences; moreover, that they were conditioned by those experiences. Prior to the operation the dogs had had to choose between two troughs, shifting accordingly to right or left. What if one trough is removed from the experiment and the classical scheme is restored?

A common "bell" reflex was developed in a dog, food was offered in this single trough, and the dog did not have to make a "mental" choice. Then the frontal lobes of the brain were removed. The dog did not pace back and forth as in the previous experiments. It sat still.

The experiment was extended, and a reflex with bilateral reinforcement, as physiologists call it, was developed. Following lobectomy the dog was fed from two troughs. After two or three such feeding sessions the dog began to shuttle back and forth.

Some conclusions could now be drawn. Before deciding what trough to approach following the signal, the dog must appraise the situation. It must understand the messages streaming in from its sense organs and internal receptors.

It must select the signals that are pertinent to the forthcoming feeding and formulate a plan of action. The upshot must be a movement towards the trough into which a piece of meat is to be placed and also a reflex salivation and excretion of gastric juices in preparation for eating.

What happens when the frontal lobes are removed? Salivation occurs according to the bell, but motor activity takes place independently of the conditioning signal. The motor component falls out of the general pattern of behaviour, as it were, and the animal's actions lack organization. It appears that without the frontal lobes the brain is unable to synthetize the various signals coming up from within and without. Each isolated signal is now capable of "firing" the whole complex of responses developed with its participation. The animal's behaviour loses its purposefulness and degenerates into a number of unrelated movements. That is why a dog picks up and swallows small objects resembling sugar or bread crusts in colour or form. It is incapable of generalization, and circumstantial resemblance is sufficient for it to take an unfamiliar object for food. But what, however, do the oscillatory movements indicate?

The removal of the frontal lobes apparently affects the brain's ability to time the various actions. The necessary movements commence too early, as if of their own accord. Lacking control from the cortex, they become automatic and stereotyped.

The fact that the more automatic a dog's reflexes were before frontal ablation, the better they were retained after the operation, confirms the physiologists' idea that the brain

strives for the greatest possible automation by handing control functions down to the lower regions.

The persistence of the oscillatory movements in the absence of food suggests yet another disorder: actions yielding food are not reinforced in the memory. Signals which could be interpreted to mean "Go or not—the trough is empty" do not reach their destination as the relevant brain area has been removed. Useless motions are therefore repeated again and again.

Nina Shumilina has studied the frontal lobes of the brain for many years. She has carried out thousands of experiments and hundreds of control tests to verify her conclusions.

Why, for instance, does frontal lobectomy primarily affect motor activity? Maybe it is simply a case of damaging the neighbouring motor area of the brain during the operation?

New dogs are prepared for a control test. This time the frontal lobes remain intact: Gypsy's motor area and Rover's visual area are removed. Both dogs display characteristic behaviour disorders. Gypsy cannot stand, her legs spread out and she sags to the ground. She must learn to walk again.

Rover also walks with difficulty, but for a different reason. His vision is impaired, he cannot tell his trough from a block of wood, and blunders into chairs and doors. Neither dog, however, oscillates back and forth and their behaviour is quite unlike that of the dogs without the frontal lobes.

Only then could Professor Anokhin and his associates declare: the frontal lobe is apparently the seat of the mechanism or mechanisms which control the synthesis, evaluation and generalization of incoming messages.

"It was long suspected," Professor Anokhin says, "that there must exist some special mechanism for synthetizing various external stimuli. While working with Academician Pavlov, I conducted an experiment with a dog named Vizgun which lasted for several years. The conditions of the experiment were such that Vizgun's responses to each stimulus were remarkably consistent, so much so that one could literally predict the amount of saliva he would secrete.

"During one test I was surprised to observe no response at all to the first conditioned stimulus. This was so unusual that, there being no sign of illness, I inspected the room in which the experiment was held for an explanation.

"I finally discovered that I had forgotten to fill the foodpan, which was concealed behind a screen, with grated crusts. As soon as I filled the gap in the established routine the conditioned stimulus evoked the usual responses and the experiment proceeded according to plan.

"What interpretation should be given to this fortuitous episode? It did not occur to me at once. Later it became clear that the exclusion of a factor with no direct bearing on the conditioned stimulus—the pouring of grated crusts into the dish—had reduced to naught the effect of the stimulus.

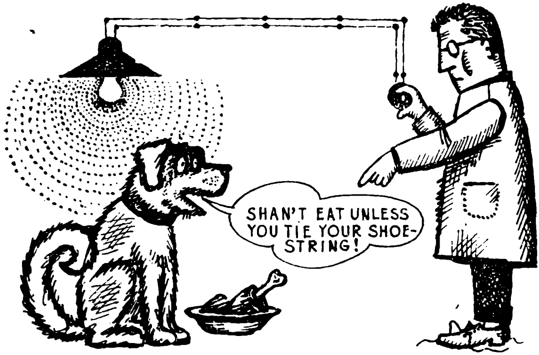
"Thus, a conditioned stimulus induces a 'food' response not only because it is itself associated with food but because it is a constituent part of the general environment, which alone can ensure a positive effect.

"This means that an animal's brain continuously embraces the totality of stimuli, including both the conditioned stimulus and those from every component of the environment as a whole."

Information concerning the environment in which an action is to take place prepares the specific response; the response is dovetailed to the given circumstances. If some appreciable component of the environment is missing there is no response.

Suppose, now, that all the preliminary information has reached the central nervous system. It does not necessarily evoke a response. When many experiments with a dog are conducted in the same room, it might be expected that in time the very appearance of the room, the lighting, the bench to which the animal is strapped, the conditions of the experiment would be sufficient to cause salivation. Yet it begins only when the conditioned stimulus is applied. It stops when the stimulation stops. Thus, in addition to information concerning the environment the organism requires a message to "trigger" the reflex. Switching on a light or ringing a bell has the same effect as pressing a button to start a machine.

Many simple processes are started by such "triggering" signals. A bell rings for lunch, for example, and you immediately feel hungry:



your stomach has begun to secrete gastric juices abundantly and you are ready to receive food although it has not yet been served.

Other actions seem hardly related to the conditioned signal, which merely triggers reflexes, just as the pressing of a single button starts the train of complex processes involved in a rocket launching or curt commands like "Hup!" or "Allez!" in a circus performance signal the beginning of a series of somersaults or cartwheels.

It thus takes a suitable combination of "environmental" and "firing" information to trigger the nerve mechanism of a reflex. If this combination is absent no reflex action takes place. The brain must necessarily receive and compare both kinds of information. Without this purposeful behaviour breaks down.

We know now that this analyser—which is a kind of brain within the brain—is located in the frontal region of the brain. There various messages are compared, logical relationships between them are established, and generalized, abstract notions are formed. These are known as the "associative areas". Another blank spot was thus removed from the map of the brain.

"Alarm Clock" and "Chronometer"

A decade or so ago a very peculiar mechanism was discovered in an otherwise inconspicuous section of the nervous system between the brain and the spinal cord. Physiologists all over the world hastened to explore the discovery, which Professor Anokhin regards as the greatest breakthrough in neural physiology in the last hundred years.

"Little did we expect to find something remarkable there," Professor Anokhin says. "Judge for yourself: there is universal interest in the higher regions of the brain, that mysterious laboratory of thinking. Much remains unexplored there and every new discovery is a revelation. Below it lies the apparently well-explored automatic nerve mechanism, or rather a system of mechanisms comprising the cells of the spinal cord. Between them lies the so-called brain stem, which joins the spinal cord with the cerebral hemispheres."

It has long been described in detail and pictured in anatomical atlases. Since Descartes' time or thereabouts it has been transferred from chart to chart with hardly a change, and no one appeared to care much about it. Its nerve cells were known, however, to be arranged neither in layers, as in the cortex, nor in knots (ganglia), as in the subcortical regions, but in a thin net covering the stem, which is why the area was called the "reticular formation".

When the American H. W. Magoun and the Italian G. Moruzzi once attached an electrode to the reticular formation the result was hardly what they had anticipated. For when the current was switched on the test monkey, which had been busying itself in one corner of its cage, looked up at the researchers as if asking, "What's the matter? What was that?" The animal was neither frightened nor irritated. It was as if an invisible being had knocked diffidently on the cortex and told the brain to get ready for something. And the brain appeared to be roused and poised in anticipation of new signals.

The reticular formation appears to act as a kind of alarm clock which rouses the cortex to activity. The "awakened" cortex is ready to sort out the

signals coming in from the sense organs and extract pertinent data from its memory store.

As soon as the results of the experiments were published the storming of the new fortress began. Removal of the reticular formation caused monkeys to fall into a permanent stupor, a kind of lethargy or narcosis. Although the brain and the nerve tracts connecting it with the sense organs and muscles were intact, the animals were unable to perform a single purposeful motion and responded in no way to the environment. It was as if the brain had been simply switched off.

The nerve fibres from the body's numerous sense receptors have lateral branches which pass through the outer part of the brain stem. The brain does not respond to signals from the body's receptors until they are followed up by an "okay" from the control centre. Only then are they perceived. This, of course, means that there must be direct nerve links between the reticular formation and the cortex. It was found that these are effected by means of nerve fibres rising from the core of the brain stem up to the brain. An unexpected discovery was that the reticular formation also has downward connections with the spinal cord. Experiments confirmed that it participates in the apparently completely automatic functioning of the spinal cord. It keeps the muscles in a state of readiness for action and initiates quick reflex movements in emergency situations. In other words, the reticular formation switches on the automatically operating reflex mechanism. More, it alters the nature of that mechanism.

A sudden sharp tap on the right place of the knee causes the leg to kick out. This is the so-called patellar (knee joint) reflex. If an electric

current is passed through the reticular formation when the knee is tapped the kick is much bigger, as if the mysterious neural mechanism had removed some inner inhibition and given the muscles more freedom of action. This happens whenever the upper part of the formation is stimulated. The lower part, on the contrary, inhibits muscular activity. Thus, the reticular formation regulates muscle contraction. Without it motions are jerky and spasmodic.

Summing up all that we know about the reticular formation, we can say that it intercepts both the messages entering the cortex and the commands it issues.

It has lately been established that besides regulating the work of the upper and lower regions of the central nervous system the reticular formation also intervenes in the flow of information to and from them. For example, it can increase or reduce the frequency of the impulses coming up to the brain from the "sense organs" of the muscles (the proprioceptors) thereby altering the nature of the information carried by them.

The reticular formation was found to affect messages coming in from all sense organs without exception. In some cases this remarkable apparatus is capable of acting directly on a sense receptor, for example it can determine the nature of sound signals in the ear itself.

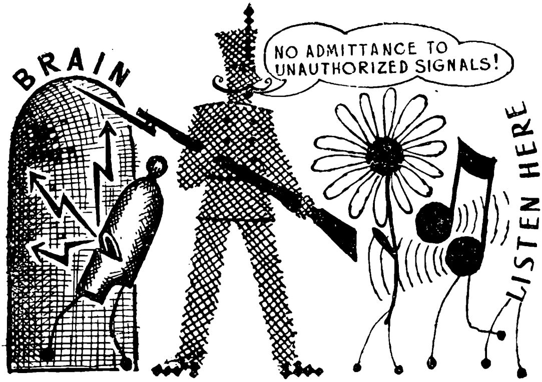
Basically the reticular formation inhibits nerve impulses, thereby reducing the volume of information coming in from the sense organs. Like a vigilant sentry, it guards the brain from intrusions of unimportant signals, reacting promptly to important messages, especially unusual ones fraught with possible danger. By screening extraneous or secondary information

it enables the brain to concentrate on more important tasks.

This is confirmed by the following observation. A dosing cat was disturbed by tapping a microphone. Its brain registered the strange noise, which appeared as a characteristic wave pattern on an electroencephalogram of the auditory centre of the cortex. Then, with the tapping continuing, the cat was shown a mouse. Immediately the electrical activity of the auditory centre dropped: the cat's attention had been diverted to the mouse by a signal from the reticular formation, which alerted the visual centre. The "mouse" stimulus being more important, the reticular formation halted the signals from the ears at the first junction in the auditory nerve pathway, letting through only just enough auditory information to keep the brain aware of the existence of a sound source of some kind in the vicinity. Thus the brain could concentrate on the more important "food within reach" stimulus.

Further investigations of the functions and structure of the reticular formation revealed many more extensive connections with various departments of the nervous system. For example, nerve fibres were found to branch from the brain stem and connect the reticular formation with the hypophysis, that regulator of endocrine activity. The hypophysis (pituitary) produces chemical substances which affect the pancreas, adrenals, the thyroid and other glands subordinated to it. These respond in turn by secreting their specific hormones which affect the functioning of internal organs.

Nearby is located another of the brain's guardians, its "chief chronometer". It does not rouse the cortex in an emergency like the reticular



formation, but it sets the rhythm, as it were, which all internal processes follow. Our body temperature, blood pressure, the number of red blood corpuscles, the gas composition of the blood, the fat and carbohydrate content of the organism, the intensity of heart, kidney or lung functioning are all subject to regular diurnal fluctuations. It is as if our body rhythms were controlled by a hidden clockwork.

Periodic changes are observed in pieces of tissue cut out of the organism and in unicellular animals. The metabolism of each cell and the size of the nucleus vary according to a diurnal cycle. It was originally thought that changes in internal processes follow the pattern of environmental changes. Our planet turns on its axis, night follows day, light and darkness, heat and cold continuously alternate. Animal organisms would appear to have adapted themselves to these fluctuations and work in step with nature.

Investigations carried out at a stationary point of the globe, the South Pole, have revealed, how-

ever, that the rhythm of our internal "clock" does not depend on the Earth's rotation. Even when an animal is placed in a chamber where constant humidity, temperature and lighting are maintained the rhythm of life continues to follow its internal schedule. The body chronometer appears to be quite independent. Attempts were made to stop it by lowering the body temperature of animals to 0° C. The "chronometer" appeared to have "stopped" and no rhythmic changes in metabolism were observed. When the animal was warmed back to life the "chronometer", too, started ticking again. Only it lagged behind the "chronometer" of a control animal by exactly the six or eight hours the test animal had been in its "cooled" state, and all functional cycles were shifted accordingly.

Scientists have come to the conclusion that the body contains a variety of "clocks". Each cell and every organ has a "chronometer" of its own. The "master chronometer" is located in the brain. It is the area in which are found the nerve centres controlling body temperature, water-salt, carbon and fat metabolism, and the functioning of endocrine glands.

To summarize. The brain stem represents a cross-roads of nerve pathways. It is the location of a "chronometer" of internal processes and a central control mechanism, which acts as a kind of guardian of the brain. It keeps the cortex alert, and maintains the activity of the automatic mechanisms of the spinal cord and all the simpler homeostatic regulators of the nervous system.

From wherever signals reach the brain—from the lungs, heart, muscles, eyes, ears, nose, etc.—they first pass through the reticular formation, which "rouses" the brain. This is very clearly

shown in electroencephalograms, which monitor the brain's electrical activity.

A stimulation coming up an auditory or optic nerve activates a specific section of the brain and does not extend beyond the auditory or visual centres of the cortex. They are of local importance, so to say.

But this is not enough to ensure the interaction between various regions without which no thinking process, such as memorization or logical appraisal of visual or auditory images, would be possible. The alerting action of the reticular formation appears to consist in preparing the way for the stimulation of cortical nerve cells. In this way it helps the brain to establish correlations between the numerous nerve signals entering different nerve centres.

Pleasure Centre

The rat is obviously pleased and literally dances with delight. What has evoked such a profuse display of emotion? I look about and inspect the metal cage, which contains nothing save for an empty feeding trough in the corner. There appears to be no apparent cause for the animal's delight.

"It is this pedal that gives it such pleasure," the laboratory workers explain.

"How come?"

"See how the rat keeps pressing it with its foot."

True enough, as it dances it repeatedly presses the pedal. I observe that a thin wire extends from its head without interfering with his movements.

"An electrode?" I ask.

"Yes. When pressed, the pedal switches on an electric current through it. Just like the other experiments where the brain is electrically stimulated, only here the rat itself can turn on the current."

"Why should it cause itself unpleasant sensations?"

"They may not be unpleasant," the laboratory workers smile.

"Do you mean to say that the rat gets pleasure from passing an electric current through its brain?"

"Precisely. The electrode is implanted in the brain's 'pleasure centre', the nerve cells of which evoke sensations of pleasure when stimulated. When the pedal is disconnected from the circuit the rat soon loses interest in it."

The English physiologist James Olds, who first carried out the experiment, wrote later that the rat in his tests preferred stimulation of the pleasure centre to food. In fact, no matter how hungry it was, it paid no attention to the food as long as it could press the pedal. In one experiment it pressed the pedal for twenty-four hours running until it collapsed from exhaustion.

By implanting electrodes in the brain at various sites and depths Olds was able to delineate the boundaries of the pleasure centre. An electrode implanted at the core of the pleasure centre sent the rat into an ecstasy of delight in which it pressed the pedal 8000 times in the course of one hour. Closer to the periphery of the area the response was not so pronounced, the rat no longer pressed the pedal with such zeal and could be distracted easier. Moving the electrode still further away reversed the nature of the response, eliciting manifestations of displeasure or fear, and the rat took care to avoid initiating the

stimulus. If this area was continuously stimulated a formerly quite tame animal was likely to turn on the experimenter in a violent rage.

The physiologist Delgado conducted a similar experiment in which he induced changes in the attitudes of two animals towards each other. He took two cats which had lived together in the same cage in the friendliest fashion, implanted an electrode in the brain of one of them and steadily passed current through it. The cat stared angrily at its neighbour and recent friend, spat and clawed at it, and finally flew at its throat. In another experiment Delgado caused monkeys of two naturally hostile species to become close friends. This was achieved by electrically stimulating deep-lying subcortical regions of the brain.

That the deep-lying layers of the brain are responsible for a person's emotional state and mood had been known long ago. The subcortical matter acts as a kind of store for "state" signals from all the internal organs. When everything is in order inside the body one naturally feels good and is in high spirits. If something goes wrong one's mood changes, one loses one's vitality and feels depressed or anxious. As Sechenov wrote, "How one feels is a kind of 'aggregate sensation' reflecting the state of affairs in one's organism."

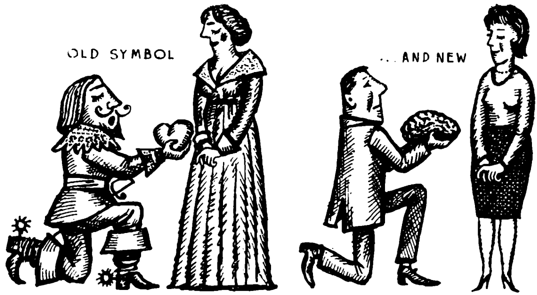
Pavlov had attached considerable importance to the subcortex, but it was nevertheless some time before it received the attention of physiologists. Of late, however, and especially after the discovery of such complex nerve formations as the pleasure and fear centres, scientists have tended to give greater attention to the deep-lying regions of the brain. They have discovered connections

between the subcortex and the reticular formation in the brain stem. In fact, the brain stem merges directly into the areas of nerve ganglia responsible for our emotions, and the "pleasure" and "fear" centres are actually located in the upper part of the brain stem. Small wonder that their stimulation induces not some specific state but a general feeling of pleasure, joy, despondency or fear. Here, too, the reticular formation alerts a specific region of the brain (the subcortex, in the present case) for "pleasant" or "unpleasant" emotions.

Sometimes, however, a strange duality is observed between the state of the brain and the behaviour of a person or an animal. If a substance called physostimine is introduced into the blood the cortex develops a state of excitation similar to that evoked by a "general alarm" signal. Yet a rabbit continues to munch its carrot unconcernedly. On the other hand, when atropine, which has a sedative effect, is introduced, electrical activity shows the brain to be "asleep", although by all external appearances the rabbit is not at all sleepy.

"One could expect," Professor Anokhin wrote later, "that the observed picture of more or less uniform electrical activity caused by the reticular formation conceals the actual extremely varied nature of nervous activity. It was therefore necessary to view the functions of the reticular formation from a different aspect."

The notion of the nonspecific action of the reticular formation was developed on the basis of experiments in which the brain stem itself was electrically stimulated. Professor Anokhin turned to the tried and tested method of conditioned reflexes in order to place the brain in as natural



conditions as possible. A conditioned salivation reflex was developed in a rabbit and electrodes were implanted in its brain to produce diagrams of its electrical activity. The rabbit was alternatingly subjected to the conditioned stimulus (a bell or a flashing light) and to a pain stimulus (an electric shock), which caused it to snatch its paw away. The cortex was found to respond to the two stimuli in different ways. Pain (and later the very sight of the harness in which the experiment was conducted) evoked a slow and uniform electrical rhythm having a frequency of 4-6 cycles per second. When the bell rang or the light flashed (the conditioned stimuli promising food) the brain responded with faster and less uniform electrical rhythms. The action of the reticular formation is not so uniform as was originally supposed.

In the next stage of the experiment, the rabbit, wearing its harness and anticipating pain, was given an injection of aminazine (chlorpromazine), a sedative. In 10-20 seconds the electrical rhythm in the brain changed and slowed down. Five minutes later the brain appeared to have calmed down, and its electrical rhythm was apparently

the same as in anticipation of food. The rabbit's behaviour changed accordingly. At first it had been nervous and had refused its favourite dish of fresh carrots. The knowledge that this was the room in which it suffered pain made it afraid, and it even snatched its paw away when a carrot was extended to it. After the aminazine injection its fear disappeared and it took the carrot. More, it continued to nibble the carrot when an electric shock was administered to its paw.

The suggestion is that aminazine switches off the centre in the reticular formation which is responsible for painful sensations, without affecting the centre which alerts the brain for pleasurable sensations. This section of the reticular formation appeared to be insensitive to aminazine. But aminazine has an antidote called adrenalin. Would it inhibit the "pleasure" centre? An injection of aminazine was followed by one of adrenalin. Very soon the rabbit grew restless again and refused to take food. The pleasure centre had "closed down". The experiment was repeated many times, and aminazine invariably inhibited the defensive responses in favour of

food responses. Adrenalin, on the other hand, amplified the former and inhibited the latter.

It thus appears that there are at least two neural mechanisms at work in the reticular formation, one being responsive to aminazine, the other to its antidote, adrenalin. The conclusion is that psychic states apparently derive, at least in part, from complex nervous processes, each one being evoked by different specific chemical substances.

"The science of the brain," Professor Anokhin says, "is faced with a new field of investigation which one might call 'emotional chemistry'. We now know for sure that all 'negative' emotions, such as dejection, apprehension or sorrow, are caused by the appearance of large quantities of adrenalin in the blood. In fact, we could define the state as 'adrenalin dejection'. Removal of the excess of adrenalin from certain brain cells prevents feelings of dejection or apprehension from developing. This is just what aminazine does."

Professor Anokhin's investigations indicate that, contrary to the notions of scientists in many countries, the reticular formation has no uniform activating effect on the brain. Rather it depends on the type of biological reaction—positive or negative—that is evoked at the time. Insofar as its functioning is chemically based, it is possible to control it by means of chemical substances: sedatives, stimulants, etc.

Nerve stimuli, we find, travel from sense receptors to the brain by two routes: directly and, at the same time, through the reticular formation. This means a new link in the conditioned reflex scheme. Professor Pyotr Anokhin set out to trace it and determine the part it plays in the conditioned reflex chain.

Reflex Circuitry

A very simple and very graphic experiment was staged. An area of a rabbit's brain was exposed and a patch of paper dipped in strychnine was placed on it. Strychnine is a powerful stimulant, and in a few minutes' time high peaks appeared on an oscilloscope screen, denoting that the excitation had spread from the stimulated section all over the cortex. How does this spreading occur, across the surface of the cortex, like waves in a pool of water or through the subcortex? To trace it, the two hemispheres of the brain were first separated. The patterns of electrical action potentials on the oscilloscope remained the same, indicating that the excitation continued to embrace the whole brain. Then the small area of the brain with the patch of paper on it was separated from the cortex. The electrical rhythms continued without change. Finally, the investigators decided to remove the paper patch and apply a piece of ice to the same place in order to inhibit the original stimulus. But although the point on the cortex ceased to flicker, other cortical centres kept up the electrical rhythm caused by it.

There could be no doubt that the specific section of the cortex which serves as a source of neuron excitation is not responsible for keeping the excitation alive. Instead, the brain sets up an excitation locus in the subcortex which keeps the cortex active by stimulating it with rhythmic pulses.

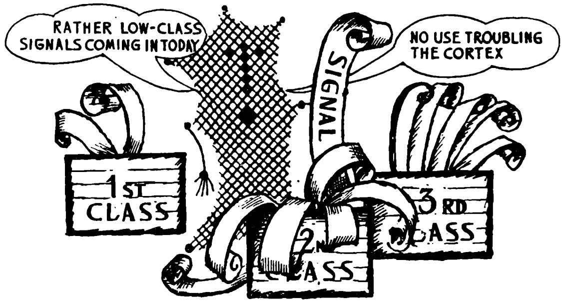
In what part of the subcortex does such an activating locus appear? In the reticular formation. This was easily demonstrated. When aminazine, which inhibits the functioning of the

reticular formation, was introduced into the rabbit's organism, cortical activity quickly subsided: the activating mechanism had been switched off.

It thus appears that stimulation coming in from sense receptors reach the cortex directly and develop a motley pattern of excited and quiescent sections. The pattern is not stable, and it would change as rapidly as the fanciful designs in the eyepiece of a toy kaleidoscope if it were not for reinforcing stimuli which reach it a few moments later. They come in from the same region as the original ones, but in a roundabout way, through the reticular formation. The latter, as we now know, screens all incoming messages, amplifies the important ones and keeps the incidental ones out.

Most physiologists agree that the reticular formation essentially comprises two nerve mechanisms with different functions. One, which covers the brain stem, is the activating mechanism, the "alarm clock" which keeps the cortex awake and ready to handle incoming messages by sending up a regular stream of activation impulses.

The other, located higher up, just between the two hemispheres, acts as a kind of projector. The cerebral cortex is a wonderful screen various parts of which are capable of perceiving pictures, music, smells or whatever the case may be. The "projector" in the reticular formation sweeps a beam of visual, auditory, olfactory or any other images across the cortical "screen". These reinforcing images, when they are projected on the appropriate section of the "screen", make the initial weak and unstable images perceptible to the brain.



Thus, one part of the reticular formation switches on before the messages have reached the cortex, the other goes on immediately afterwards and acts as a powerful reinforcement. Both mechanisms are controlled by the cortex. It makes them choose the signals it needs. In other words, it is as if the cortex establishes criteria of evaluation for the reticular formation's guidance and sets the "alarm clock" for the time it needs. Areas controlling the reticular formation have lately been discovered in the frontal lobe and around the superior temporal gyrus. Their stimulation, even by a very weak current, causes a sleeping animal to wake instantaneously. Much more powerful stimulation of other sections of the brain elicits no such response. Observations reveal that these areas send down a tremendous number of nerve impulses to the reticular formation, almost as many as enter the cortex from the sense receptors.

The leading role of the cortex in all cerebral processes, including the establishment of temporary pathways between nerve centres, has thus been confirmed. In fact, it would be useless for nerve circuits to be set up at lower

levels before a stimulation has been perceived by the brain and acquired biological meaning.

"The results obtained," Professor Anokhin writes, "suggest that the balance between the cortex and subcortex is always shifting, but in all changes the cortex never loses control over the subcortex."

Very subtle experiments show that the circuitry of conditioned reflex chains may vary even in the course of a single day of experiments. Ivan Pavlov allowed for three possible variants of conditioned reflex circuits: between two points in the cerebral cortex, between the cortex and subcortical ganglia, or finally, a nerve stimulation may pass from a certain centre in the cortex, through the subcortex and back to another region of the cortex. The type of circuit would depend on the specific conditions in which it takes place, the state of the nervous system, and other factors which cannot always be accounted for.

Now we have a new concept of the nerve circuitry of a conditioned reflex. The topmost part of a reflex arc need not pass through the cortex and if required it can be directed through a lower level. Accordingly, a firmly rooted, virtually automatic conditioned reflex circuit may lie completely in the subcortex, leaving more room for new connections in the cortex.

The cortex retains the superior role of overseer. Strictly speaking, it controls nothing by itself. In Professor Anokhin's words, the cortex "merely states its claims to the normally precisely functioning lower apparatus". These claims may vary according to the external stimuli and the general behavioural reactions of the organism at any given time.

By tracing the routes of conditioned reflex circuitry Soviet workers have solved one of the basic, and undoubtedly one of the most difficult, problems of brain physiology. The next step is to learn how this circuiting takes place and what makes individual nerve cells join up to form a temporary pathway for nervous stimuli. For this the brain cells themselves must be thoroughly investigated.

Voices of Neurons

They have many different voices, they cackle, click, squeak and hiss, they grunt peevishly when an electrode pricks their shells and squeal when it pierces them through. I thought that it was really wonderful to be able to hear separate cells of the brain "speaking up" for themselves. This is another wonder achieved in Professor Anokhin's laboratory.

The laboratory assistant, who can pinpoint neurons with the tip of an electrode, draws my attention to the green oscilloscope screen with bright zigzags of light racing across it; I cannot help marvelling that neurons can be made to answer puzzling questions with their own "voices". I continue to listen to their muted complaints and loud vociferations and want to understand what they are saying.

"Has anyone tried to interpret their sounds?" I finally ask. My guide seems bewildered. She is so used to the fact of "neuron talk" that at first she doesn't grasp my question.

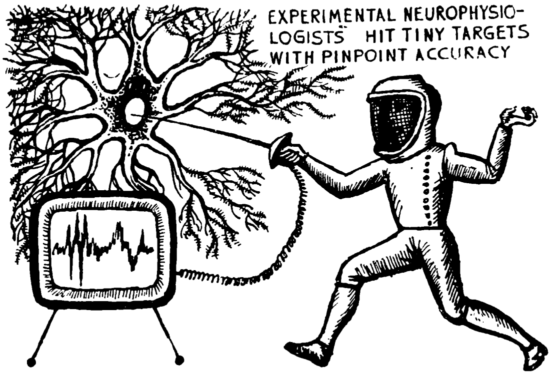
"Why no," she finally says with a smile. "It is a purely incidental phenomenon. Our purpose is to find out what goes on inside nerve cells in

stimulated and quiescent states. We hope to achieve this by studying their electrical responses. The oscilloscope curves here reflect the electrical discharges occurring inside the neurons themselves. This is the real voice of a neuron, and it gives us an idea of its state of rest, work or relaxation at a given moment."

In physiologists' laboratories one hears so much about action potentials and electrical rhythms generated by the body's organs that one gains the impression that, what with muscle action potentials, electrocardiography and electroencephalography, all body functions can be reduced to electrical activity. One might easily assume that our bodies are literally charged with electricity and that electrical impulses run up and down the nerves and electrical discharges crackle within nerve cells.

Actually, though, nerve and electrical impulses are basically different; the electrical phenomena accompanying a nerve impulse are merely incidental. Similarly, electrical discharges at the surfaces of nerve cells are simply the result of internal chemical transformations. Nevertheless, the electrical rhythms of the brain give us a convenient means of observing its inner workings.

In conventional electroencephalography electrodes are attached to the scalp. The resulting "brain wave" is evidently a quantity averaged over a more or less large area and the "voices" of individual cells are drowned in the uproar, as if a microphone were placed in the midst of a babbling crowd. A lone voice may get over if someone passes by the microphone, but if we want to hear a person's views we must make him speak into it.



In the case of the brain this is easier said than done. Try and find the specific cell you would like to interview from among a population of 14,000 millions! The job of "interviewer" must be a delicate one indeed. This is where maps of the brain come in handy. The worker locates a point of interest and calculates its coordinates to determine the site of the brain probe. A small hole is drilled in a rabbit's skull through which an electrode is lowered to the cell to be studied. An error of microns is sufficient to miss the target. The top end of the electrode is about as thick as a hair. The tip is quite invisible, being some 50 microns, or 0.05 millimetre, thick, and requires a special technique to sharpen it. Separate cells are studied with glass electrodes only two to four microns thick which occupy no more than one-hundredth of a cell's surface.

A gossamer electrode enters the brain. Its passage through the cortical tissues is accompanied by a high-pitched squeaking noise. An even crackle announces that it has come to a halt.

"We'll pierce the cell wall," the laboratory assistant explained, "and have a look, so to say, at what's going on inside." She turned the adjusting screw for positioning the electrode and the grunting noise grew louder; sharp peaks quivered on the oscilloscope screen. "Now we pass through the cell." She turned the screw again, bringing the tiny electrode into another level of the brain.

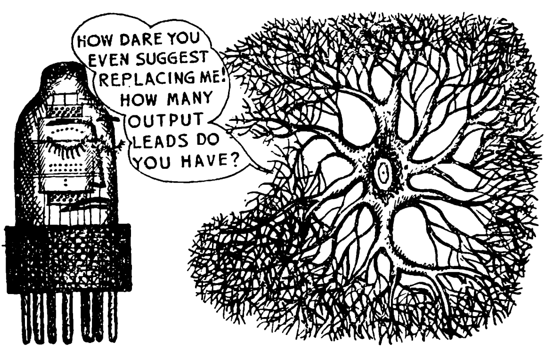
In this experiment the electrode was a passive observer of events. In other experiments several microelectrodes are planted into one cell. An electric stimulus is applied through one, the others report the cell's responses. This is an important step forward in cell study as compared with passive recordings of neuron activity. Moreover, as Professor Anokhin writes, "today no site in the brain, none of its 14,000 million cells, is closed any more to the investigator."

A most interesting discovery was made at Professor Anokhin's laboratory, which is pioneering investigation of the functioning of individual brain cells. A microelectrode was applied to a cell of the reticular formation. The electrical discharges indicated that the cell was functioning normally. Then aminazine was injected into the blood of the test animal. In five or six minutes the cell's activity began to drop, the electrode picked up fewer and fewer electric charges, and finally the cell lapsed into silence. This, of course, was hardly surprising as the electrode was implanted in the region of the reticular formation sensitive to aminazine. The drug inhibited the nerve centre, and the cells there, quite naturally, stopped functioning. But when the electrode was shifted by a mere 50 microns, that is, to a neighbouring cell, the clicks and crackling resumed and the oscilloscope screen came to life. This

meant that the cell was functioning as if nothing had happened, that the aminazine, in other words, had not affected it. Its chemical composition must therefore be quite different from that of the first cell.

This experiment, repeated thousands of times with many different variations and with various substances, placed physiologists in a quandry. For it was contrary to the concept of a nerve centre as comprising hundreds and thousands of neurons and functioning as a single mechanism. Every nerve centre was found to consist of many different kinds of cells of varying chemical composition. The beautiful picture of the brain carved up into fifty areas proved to be too simple and approximate.

Recent investigations reveal that some reflex actions of man may be triggered by the stimulation of a single nerve cell. Take such a simple case as thirst. Depending on circumstances, a "thirst urge" will cause one to engage in a wide range of activity: take a pail, find a well, lower the pail into it, draw the water, etc. If one is



camping out somewhere in the open the thirst urge may elicit considerable effort and inventiveness to get a drink of water. Yet it all begins when one or two cells of the brain that are sensitive to water shortage in the blood are activated, triggering millions of other neurons into action. The whole brain gets down to work: recalling how thirst had been quenched on previous occasions, comparing them with the present circumstances, and devising the best ways of getting water. A single tiny element several microns in diameter, not a big thirst centre, is what activates the intricate machinery of the brain.

Neuron specialization in the brain appears to be rather refined. Thus, one type of neuron responds mainly to incoming stimulations. Another establishes the general patterns in the stimuli and on this basis generates nerve impulses which, as it were, anticipate the strength, rhythm and other characteristics of new stimulations which may be expected to reach the cortex. Finally, a third type of neuron compares the excitation impulses of the first two and fires only if they do not coincide, i. e., if only one of them is in an excited state. In other words, it responds to disagreement between the predicted and actual signals.

Neuron Junctions

It should be noted that the nerve structures participating in the communication pathways and reflex chains vary depending on circumstances. It is not just a case of switching over between old circuits. New nerve circuits are developed

continuously, and the success of an undertaking will depend on how good they are. Knowledge of the kind of neuron structures that develop in the brain in various contingencies is as important as knowledge of the chemical composition of various nerve cells. As Professor Anokhin writes, "Just as the same kinds of bricks and cement can go into a Gothic or Empire style structure, so the world of complex processes within an individual cell may enter into the millions of different architectural styles of human behaviour."

Originally physiologists had been concerned mainly with cells, ignoring the nerve pathways connecting them. This proved to be a major error, and they soon had to extend their investigations to the neuron circuitry of the brain.

A vertical cross section through one of the microscopic brain storeys reveals a surprising sparsity of neuron population. Most of the space is occupied by the "internal wiring", by what would appear to be auxiliary communication pathways between cells. In fact, the cell body of a neuron occupies only a fraction of the space taken up by the branching thread-like projections (processes) growing out of it. Every neuron has one particularly long extension, called the axon, which reaches out through many cortical storeys and sometimes far beyond. The short processes, known as dendrites, are bunched around the cell body or extend a short way within one "storey".

When physiologists traced the processes of major cells in and around the visual area of the cortex they found that the neurons were closely interconnected. Therefore, when a stimulus comes in along an optical nerve fibre it spreads along the branching processes and covers a considerable

area. Similarly, motor commands do not travel straight down to the muscles. They first spread through nerve pathways to other parts of the cortex. It has been definitely established that the sensory and motor nerve fibres of the cortex form a close-knit unified network. This is contrary to the formerly held concept according to which the input and output leads to the areas where the incoming information is processed were sharply defined. The demarcations of the brain are by no means definite. It would be more correct to treat the brain as a general-purpose mechanism made up of 14,000 million parts of different kinds which work together in close harmony.

Some aspects of the internal structure of this mechanism are gradually coming to light. Thus, not all nerves have long processes. The higher an animal on the evolutionary ladder, the greater the number of "crew-cut" neurons in its nervous system, and in the human brain more than half of its 14,000 million cells are of this "modern" type. They appear to act as supporting cells that direct nerve impulses from the receptors to the cells which use the information for drawing up control commands. These supporting cells (known as neuroglia) are probably more than simple relays. They act in some way on the neurons to which nerve impulses are directed, lowering or raising their excitation threshold. Thus they not merely control the flow of nerve impulses but also influence the strength of a nerve excitation and, in the final analysis, the functioning of the cortex.

How do nerve impulses travel from one neuron to another? For at no point do the processes of one cell actually join the processes or body of another. Instead there is a gap between the ends

of adjoining processes, and it is across this gap, called a synapse, that a nerve impulse passes, just as an electric spark may jump across a gap between two electrodes. The synapse, whose name is derived from the Greek word meaning "to fasten together", acts as a switch which determines whether a nerve impulse will travel in a given direction or not. Synaptic junctions occur in a variety of ways. In the most common type the flat end of a nerve fibre from one neuron adheres to the membrane of another. The contact may also be effected by a fibre end branching into a fine lacework on a cell body. Processes from one neuron may also form synapses by butting on to the processes of other neurons.

Back in the nineteenth century investigators had noted that many dendrites along which nerve impulses reach a cell are covered with a fuzz of tiny projections. It was assumed that their purpose was to absorb nutrient substances, and the researchers did not give them much attention. Now it is known that these fuzzy growths represent a type of synapse by means of which nerve impulses are switched to a neuron from a neighbouring cell. Finally, in some cases impulses are conducted between touching nerve fibres without synaptic connections, thus providing additional communication pathways between cells.

The discovery that there are several types of switches in the cerebral cortex was made fairly recently. This is not a case of different types of cells being provided with different kinds of switches. One cell usually has several kinds of synapses. Evidently, there must be some reason for this. Sure enough, the various types of synapses were found to differ chemically as well.

Substances have been discovered which have a specific effect on the different types of switches without affecting the neurons themselves. The suppression or inhibition of only a few synapses can alter the nature of a conditioned reflex or even cause psychic disorders, though the nerve cells may remain intact.

Brain physiologists are currently giving special attention to this delicate mechanism. Their interest lies not in the nerve cell or in its processes, but in the wonderful switching system of the brain, and this is being studied in great detail at the Brain Institute in Moscow.

Synapses are connections by contact. The nerve processes do not "grow" into one another, they are not "grafted" to a cell body, their living matter does not mix, there are no holes or cracks through which the nerve impulses could pass. Yet pass they do. More, some synapses do not have direct contacts between fibres, yet the nerve impulses jump across the intervening space. In other words, nerve processes can interact at a distance. But two bodies can interact at a distance only if there is a physical field of some kind between them—electrical, magnetic, etc. It would appear that neurons "induce" fields just as electric current in one coil of a transformer induces current in another some distance away.

This is the conclusion drawn by Professor Semyon Sarkisov, director of the Brain Institute, who has headed research in this field for many years. His latest investigations are devoted to the fine neuron structure of the brain.

It was in his laboratory that I first saw what a neuron really looks like in all its details: the small cell body is lost amidst a tangled mass of dendrites.

"You journalists like to compare neurons with electron tubes," Professor Sarkisov remarked to me. "But how many leads does an electron tube have? Two, four, at most eight. Do you know how many leads an ordinary nerve cell has? Tens, and maybe even hundreds, of thousands. And every lead has tens of thousands of different kinds of switches. Each one does its particular job, and you can be sure that the right one will click. There are no mix-ups, no errors. This is reliability for you.

"It is utterly wrong to compare this intricate, perfect structure with an electron tube! It is here that the secret of the brain's reliability must be sought, the secret which is the cybernetician's dream."

The Boons of Redundancy

Alexander Berg, leading Soviet cybernetician, also stressed the problem of reliability. In fact, he says, reliability and maintenance are the greatest problems in electronic engineering and industrial automation. The failure of a single switch or other component out of hundreds of thousands puts an electronic machine out of order.

All the more cause to envy nature's ingenuity in solving the key problem of reliability. The human thinking machine operates without a hitch for decades, the organism is continually subjected to harmful effects which tend to unbalance the efficient operation of the central nervous system, and not infrequently individual nervous mechanisms sufier irreparable damage. Yet the brain continues to maintain the body's living functions. If we could only achieve something remotely approaching "living automatons" in performance!

What are the spare parts which nature has provided in case of a malfunctioning in the nervous system, what ensures the harmonious operation of 14,000 million neurons?

In the days before cybernetics, physiologists never even thought in terms of reliability. They had no use for such a purely technical term. Cybernetics forced a new attitude to the problem. One of the results of this new approach is a book called *The Reliability of the Brain*, written by Ezras Asratyan, a leading Soviet physiologist, director of the Institute of Higher Nervous Activity, and Pavel Simonov, a research worker at the institute. The book reads like an exciting novel. The Institute of Higher Nervous Activity studies problems relating to the cure of disorders of the central nervous system. One would think that workers engaged for more than a quarter of a century in studying the adaptive mechanisms of the brain need no longer wonder at the remarkable viability of the nervous system. Yet they continue to wonder. "The ability of the brain, especially its higher regions, to restore disordered functions," Asratyan and Simonov write in the foreword to their book, "baffles the most vivid imagination."

We are already acquianted with one of the brain's rehabilitative mechanisms—the "retraining" ability of nerve centres. Hundreds of experiments on cross-connecting nerves, like those carried out by Professor Anokhin, were performed at the Institute of Higher Nervous Activity. The result was always the same: the damage was rectified, and the tactile centre, for example, was made to control leg motion while the motor area controlled stomach contraction. The nerve centres of the brain lost their original specialization

and learned to perform new functions. The animal adapted itself to new conditions. A dog with an amputated leg has no difficulty in learning to walk on three legs. A rat deprived of the use of all four legs soon finds a way of wriggling and rolling over to get to its feeding trough.

These and many other experiments reveal the remarkable ability of the cortex to set up new reflex pathways in extreme conditions such as could not be anticipated in normal animals. The flexibility of the cortex, its adaptability to all kinds of functions enables living organisms to survive in many extremely difficult situations. It would appear from what has been said that an animal deprived of the cerebral cortex would be incapable of adaptation and would inevitably perish. Let us see if this is so.

In one experiment at the Institute of Higher Nervous Activity the cerebral cortex was removed from both hemispheres of a dog's brain. The dog's behaviour after recuperation changed markedly. It neither responded when called by name nor recognized its master. It lost its ability to develop reflexes. Thousands of external stimuli which had formerly evoked active responses became meaningless. It paid no attention to its eternal enemy, the cat, it didn't react to the barking of other dogs nor did it investigate an opened door. It could have starved to death in a room with pieces of meat scattered all over the floor and pans of mush in every corner.

Perception of the surrounding world had deteriorated markedly, but the dog did not lose its ability to move. It paced the rooms for hours, avoided sharp and hot objects and even chewed meat shoved into its mouth. The behaviour of an animal deprived of the higher regions of the

brain is guided by the simpler automatic regulators, the basal ganglia underlying the cerebral cortex.

In the next stage of the experiment the spinal cord was severed, paralyzing the hind quarters. Signals from the basal ganglia no longer reached the hind legs and the dog dragged them along the ground. Yet an electric shock caused the dog to pull its leg away, indicating that spinal cord centres below the severed point had responded to the stimulus.

Finally the nerves leading from the activating centres of the spinal cord to the leg were severed, removing the final link between the nervous system and the muscles. Now the leg remained motionless even when given an electric shock or pricked with a pin. And yet the muscles had not lost their ability to contract. A remarkable thing happened: left entirely on its own, with all connections to the nervous system gone, the muscle became more sensitive to chemical stimuli. The ancient mechanisms of chemical control came to life and assumed control functions. These primitive mechanisms which evolved millions of years ago are latent in the highly organized bodies of higher animals and have not quite lost their functional abilities. They remain as a kind of reserve which assumes control functions in extraordinary circumstances, when the supreme controls break down.

Of course, these "other ranks" of the nervous system lack the broad outlook of the "supreme commander" and are incapable of marshalling the whole army of cells in our bodies. Acting on their own, however, they can maintain the "fighting ability" of their respective "units" until reinforcements from the centre arrive.

That is why a heart removed from the chest may continue to contract for hours if local blood circulation is provided. The blood vessels in a rabbit's ear whose nervous connections with the organism are severed constrict and dilate when chemical stimuli are introduced into the blood.

Such emergency replacements probably explain the reason for the multistoreyed arrangement of the central nervous system. The relative independence of each level along with strict subordination to the higher control centres is the basis for the brain's reliability. The lower levels of this hierarchic ladder, which do not participate directly in the control functions, could well have been discarded long ago as useless, yet the organism retains them as an emergency last resort. Multiple duplication enables the functions of damaged links to be transferred to other levels. However imperfect such substitution might be, it keeps the organism alive.

In addition to such storey-by-storey duplication the brain has another kind of reserve system. It was long ago observed that removal of the visual area of a dog's cortex does not result in complete loss of sight. The dog skirts obstacles, turns towards a bright light and can even develop a conditioned reflex towards light. Similar phenomena are observed when the auditory centre is removed. Animals continue to discriminate between loud and weak sounds, between a musical tone and random noise.

The impression is that in these cases reserve nerve centres come into operation. They cannot replace the main ones completely, their responses are coarser and more primitive, but they enable an animal to retain a degree of sight and hearing.

Subtle experiments have revealed, sure enough, that besides the main visual, auditory and other sense centres there are minor sense areas scattered throughout the brain, some of them pretty far away from the main centres.

Detailed topographical maps have been drawn showing the main nerve centres and their outlying departments which lack precise boundaries and comprise cells located in different parts of the brain. It was incidentally found that some nerve centres are not "centres" in the true sense of the word. Instead, the corresponding functions are carried out by separate cells operating quite independently. This is particularly true of the mechanism controlling the internal organs.

There are undoubtedly good reasons for this. For one, thanks to such an arrangement, the heart, lungs or stomach are able to interact with quite different sections of the cortex with equal success. Secondly, multiple duplication or redundancy of the nerve cells responsible for the functioning of the same internal organ ensures a greater reliability in the control of such vital functions as breathing, blood circulation or digestion.

We probably still have much to learn about the protective devices of the central nervous system and all its possibilities. When one-half of a dog's spinal cord was severed this, naturally, caused some grave disorders in the organism and the dog could neither walk nor even stand. One could hardly expect to see any marked improvement in its condition. Judge for yourself: nerves practically do not regenerate. Nerve fibres can grow, but they cannot pierce the scar caused by a lesion. The nerve cells of the spinal cord destroyed in such an operation generally do not regenerate at all. It would seem, therefore, that the dog was

doomed to permanent invalidity. But in time it learned to move about, and soon it was as lively as if nothing had happened. The conclusion is that the spinal cord has reserve fibre tracts and nerve cells which can replace damaged ones. Such supplementary nerve pathways have in fact been discovered. At the same time, of course, the brain cannot rely on redundancy alone and it must be able to repair damaged parts as well as prevent breakdowns.

Up till now we have been speaking of only one aspect of cerebral activity—stimulation of nerve cells. The firing of a nerve cell is followed by a brief period of rest in which processes inside the cell are inhibited. Stimulation is always followed by inhibition. This is easily observed. If the brain area controlling the flexion of one of the arm joints is stimulated with electricity, and if a second stimulus is applied just 13 seconds after the first, it evokes no response. The nerve cells are "resting" and they do not transmit commands to the muscles. If the interval is greater than this, the muscles contract without fail.

The brain uses such brief inhibition periods for "running repairs". This contributes to the remarkable efficiency of the nervous system which we find so amazing. But the brain also finds time out for more extensive repair work. "Every night," Asratyan and Simonov write, "nature halts our brain for what amounts to a complete overhaul."

During sleep the whole brain is inhibited, the nerve cells rest, accumulate energy and restore their working ability. Deprivation of rest results in dangerous overexcitation which can lead to the complete exhaustion of the nervous system.

In emergency conditions nerve cells may be inhibited even when awake. This happens when a stimulus is too powerful. Thus, if a bell causing a salivation reflex in a dog is allowed to ring too loudly salivation stops. This means that the nerve cells of the auditory centre have been inhibited to protect them from damage.

Experiments demonstrate very clearly what threatens the nervous system if the inhibition is insufficient or has no time to develop. Rats were subjected to powerful and frequent sound stimuli. Normally this has no ill effects as inhibition raises the excitation threshold of the nerve cells. But if a very brief interval occurs between signals, a very high excitation develops in the nervous system. During the pause the inhibitory protection of the nerve cells is removed, making them defenceless when the sound is suddenly resumed. Such overstimulation of nerve cells has occasionally resulted in the death of an animal.

The kind of inhibition which develops to counteract a very powerful stimulus is called protective or transmarginal. Another type of inhibition shields nerve cells from weak, accidental stimuli. Thus, a dog will pull back its paw only if an electric shock is powerful enough, i. e., if it is above the excitation threshold.

Processes taking place within a nerve cell are restricted in this manner on both sides, as if by protective barriers. This enables it to operate at a constant, stable level.

It is all very well to know how the brain copes with internal damage. But of no less interest is how it operates so reliably under normal conditions. How, for instance, does the brain keep from making mistakes?

In a computer one malfunctioning of a single tube, with the resulting appearance of, say, "zero" for "one", will reduce to naught the results of many hours of computation. Problems solved by computers may involve more than ten million operations comprising 10,000 million elementary arithmetical operations. A correct answer requires that not a single error be made in the course of all these 10,000 million operations. In other words, the probability of an error should not exceed one in 10,000,000,000.

The late John von Neumann was the first to show that the main thing in computer operation is not so much the infallibility of each electron tube as their joint action. Mistakes are best avoided by means of repetition. Such a method of computation control is based on the mathematical law according to which the probability that two independent events will coincide is equal to the product of the probabilities of each of them. In other words, if the probability of a single computation being wrong is 0.01 per cent, the probability that an independent repetition will be wrong is $0.01 \times 0.01 = 0.0001$, that is, one ten-thousandth of one per cent. This means that with double calculation an error will be detected in 9,999 cases out of 10,000.

How can this rule be used in computer design? One way is to divide a computer's arithmetic unit into two identical and independent parts. The computation results must continuously be compared in a special device. As long as they coincide the work goes on. When a discrepancy arises the machine stops and sounds an alarm. Better still is to have three or five arithmetic units connected to a common control unit, which von Neumann called a "restoring organ", in which

"vote takers" decide "by majority vote" whether a computation should continue or not. With many such parallel devices there is no need to halt the work as the probability of all of them making the same error at the same time is negligible.

Everything thus hinges on the construction of the restoring organ. Von Neumann suggested a random connection between the computer outputs and the restoring organ's inputs. What matters is not any special circuiting principle but the number of connections. If it is sufficient, the restoring organ fires. The vote-taking decision is a purely statistical affair.

Von Neumann died without suspecting that his idea had long ago been implemented by nature. Our brain has a great deal of redundancy in its structure. Not for nothing is it divided into two hemispheres, with simultaneously functioning auditory, visual and other centres. Every nerve cell is very much like von Neumann's restoring organ. Tens of thousands of dendrites from neighbouring neurons butt on the surface of every cell. A cell fires only when a stimulation reaches it simultaneously through several inputs. Before undertaking an action the brain sums up the various impulses. This makes it a reliable mechanism, even though it is built of elements easily subject to error or breakdown.

The brain is in many respects the engineer's as yet unattainable ideal. This is especially true with regard to its reliability, capacity and negligible power consumption. The engineer's wildest dreams still fall far short of what nature has attained through millions of years of evolution.

Electronic Brains

Until fairly recently it was widely held that almost the only difference between the living, thinking brain and an electronic computing machine lay in the size and number of the cell or tube elements. At least, this was one of the main arguments advanced in most books discussing the relative similarities and dissimilarities of the two systems.

"Can one ever hope to create a machine," many authors asked, "that would have as many electron tubes as there are nerve cells in the brain? Even should this be possible, how much space would such a machine occupy?" According to one estimate it would take New York's Empire State Building to house it and a Niagara Falls of water to cool so many electronic tubes effectively. This estimate has repeatedly been cited as proof that the distance from machine to brain cannot be bridged.

It will be a long time indeed, says Warren McCulloch, an eminent expert in cybernetics, before our machines will ever begin to approach the brain, which occupies a volume of 3 pints, weighs 3 pounds, consumes 25 watts of power (as much as a small electric bulb) and has a memory storage capacity of one million million bits of information.

But here is what Vladimir Siforov, corresponding member of the Soviet Academy of Sciences, wrote in December 1961:

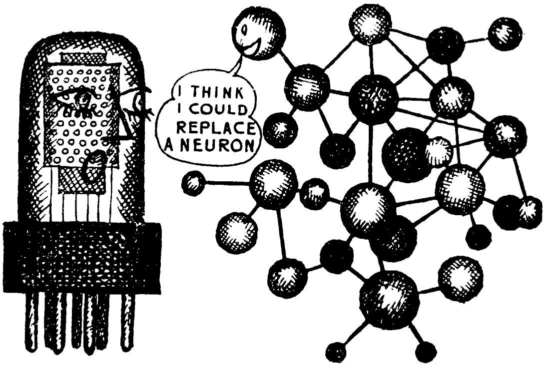
"It is safe to expect that progress in microminiaturization will make possible the construction of neuron models with as many as two hundred million components packed into one cubic centimetre of space. This approaches the packing

density in the brain (the present figure for electronic computers is smaller than this by a factor of 100,000).

"Prospects are opening up for the development of new cybernetic systems with memory storage capacities equalling that of the human brain."

The distance, it appears, can be bridged. It was reduced substantially when semiconductors and then micromodules began to replace electron tubes. Nerve cells in the brain do not function like separate "capacitors" or "resistors". The idea was accordingly suggested that electronic systems, too, could be built of general-purpose elements. This is being done by using pure crystals of semiconductors "doped" with molecules of other substances which act as resistors, capacitors, etc. Electronic components are currently being developed on the molecular level, and the new science that has emerged from this development has been called molecular electronics. The ultimate goal is to develop components no bigger than nerve cells in size. These could be used to build an artificial brain as small as the living brain. But is this sufficient to bridge the gap between the two?

Let us try and work this out. Size is only one-quarter of the job. There is no doubt that an electronic circuit fitting into a small box would be a great step forward from today's "giant brains". But as we know by now, the design of the brain is more important than size. If engineers ever hope to build even an approximate analogue of the brain they will have to turn to nature for more advice. They will have to devise electronic analogues of Professor Anokhin's action acceptor, the reticular formation, the mechanism for extracting information from the memory and so



on. Methods of memory storage will have to be remodelled along "humanoid" lines; the separate memory unit used in modern computers must be replaced by a sort of distributed store "on the job". The neuron analogue will have to be constructed in such a way as to prevent the whole system from breaking down because of a failure in one element, as often happens with electronic hardware.

Studies of the speed with which an excitation spreads through the brain seem to indicate that neurons form groups or ensembles. A nerve impulse passes at once from one cell to many or all members of the ensemble to which it belongs. How many neurons form an ensemble is not known. Some scientist say seven, each neuron being connected with three neighbours; others hold that an ensemble comprises as many as 10,000 neurons each of which is connected with at least hundreds of neighbours; others still simply deny the existence of neuron ensembles.

In one experiment to test the "ensemble" hypothesis an IBM-107 computer was used to simulate an ensemble of 63 neurons. Each "neuron" consisted of one tube and was joined with eight others. When several tubes were activated from a quiescent state the excitation spread to the whole ensemble in one-150,000th of a second. Many other experiments with neuron analogues were carried out. The electronic devices simulating neurons in computers have been called "neuristors" (*neur*on + trans*istor*). A neuristor is a much closer nerve cell analogue than an electron tube. In addition to its two states of excitation and rest, a neuristor, like a nerve cell, possesses a firing threshold which must be reached before it is activated. Also like a brain cell (and unlike an electron tube), a neuristor must rest after an excitation and gather energy for a new stimulation. Neuristors are made with eight to ten input and output leads with varying functions, some carrying reinforcement and others inhibition.

A machine utilizing neuristors is a much closer analogue of the brain than a conventional electronic computer. Electronic brains have undoubtedly grown more "intelligent" and acquired certain characteristics of living organisms, such as the ability to accumulate experience and to "memorize" states that are followed by reinforcing stimuli. Conversely, after a while they may cease to respond to stimuli that have not been duly reinforced. Does this mean that machines can become capable of discriminating between what is good or bad for it—of thinking, in other words?

Let us postpone the answer to this question for the time being and first see what is meant when one says that a machine can "acquire experience".

IV. IF MACHINES WENT TO SCHOOL———

"Insect" Machines

One of the basic concepts employed by physiologists is that of the reflex chain. The meaning this term conveys is essentially that of "operational routine" (which should not be interpreted to signify that machines, too, possess reflexes, as some of the more extreme cyberneticians claim).

The operational routine or programme of an electronic machine comprises a series of commands or planned actions. The signal initiating one action depends on the results of the preceding action.

Animals "operate" along similar lines. In response to a conditioned stimulus they perform a reflex motion, which results in a change in the environment. Information about this change tells the organism that it can proceed with the next action.

To be sure, living organisms have different kinds of programmes. Some, arising from the simplest adaptive requirements, have evolved

over many generations. They are implanted in the nervous system by nature and are inborn, hereditary programmes responsible for all unconditioned reflexes, from pulling a paw away from a source of pain to swallowing, breathing and digestion. An animal does not have to learn them, the nervous system already knows how to act. Actions under such a programme are automatically triggered by the relevant external signals, such as pain, cold, etc. Many living organisms, insects, for example, are guided solely by such hereditary programmes.

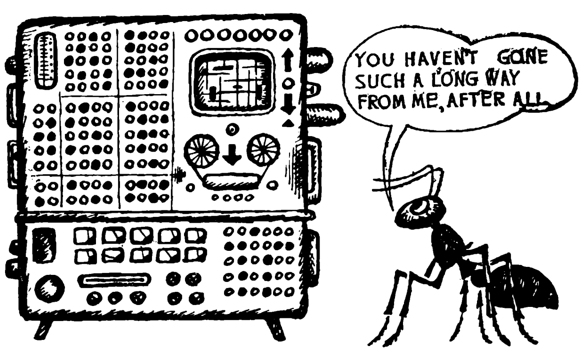
Other programmes are acquired as a result of living experience. You have probably guessed that they correspond to conditioned reflexes. They, too, are impressed on the nervous system, but they last only as long as they are of use. When the need passes they disappear without a trace, like a recording that is erased from a magnetic tape.

Electronic machines operate according to strict, detailed programmes from which they cannot deviate by one iota. Such rigidly programmed self-governing machines are like insects, which remain "weavers", "spinners" or whatever the case may be all their lives. They can be used to control processes with great precision and reliability. But for a machine to be a good blast-furnace operator, marshalling yard dispatcher or book-keeper many people must spend days and weeks describing long sequences of operations which the machine later performs so brilliantly.

Electronic systems are growing out of their children's clothes before our very eyes. They can do many things, but the greater their possibilities the greater their dependence on human beings, and as in any competition between manual and

machine labour, the former is bound to lose. The difficulty was resolved by constructing machines for programming the work of other machines, thereby mechanizing and automating a labour-consuming job. But a programming machine can do no more than carry out its own programme. It introduces no creative element into the process. If circumstances require a change in the operation of an automatic system (for instance, the change-over of an automatic dispatcher from a summer to a winter schedule), an electronic programming machine can do nothing and a human operator must enter the job.

The engineers wanted something better, something like a self-regulating machine dispatcher which would handle operations at a marshalling yard in such a way as to ensure that trains are always unloaded on time, that trucks are always loaded to full capacity, that no empty trucks ever leave the yard, that haulage costs are always minimum, etc. Such a machine should be able to draw up and carry out its programme completely on its own, including adaptation to seasonal



and other changes. It should be able to analyse its programme and improve it. But for this a *learning* machine is needed.

"Vertebrate" Machines

In his book, *From the Human Brain to the Artificial Brain*, written several years ago, Paul Cossa, the eminent French neurologist, listed what he regarded as the inherent limitations of a machine, which make it different from the living brain. "A machine," he wrote, "is incapable of learning, critically evaluating or improving the results of its work, it is incapable of generalization and it cannot invent anything new."

A year after these words were written, a large audience at Harvard University saw an IBM-704 computer choose the one and only programme suitable for solving a given problem from a variety of programmes, including several meaningless ones, fed into it. After scanning the programmes at random the machine persisted in using the requisite one. More, when the problem conditions were changed somewhat it adapted the programme to the new task instead of going through all the programmes again, thus providing graphic proof of its ability to learn.

In another development the machine was programmed to produce abstracts of scientific articles. It scanned an article word by word. From the frequency with which the various words occurred the machine determined their relative importance. Then it analysed sentences as a whole and determined their value according to the significance of the component words. Finally it typed out the

sentences judged most important and capable of conveying the essence of the paper in a brief abstract. Thus the machine met Paul Cossa's second stipulation and proved its ability to undertake a critical analysis of a text and select the most significant passages.

That same year (1958) the American Mark-1 machine displayed an even greater ability for learning when it was "taught" to distinguish a square from a circle. It thus could classify two basic geometrical figures, and it recognized a square as such irrespective of its size or colour. This meant the passing of yet another hurdle, for on the basis of specific black or red, big or small squares the machine had developed the concept of "square" as a geometrical figure. Some people saw this as an indication that the time would come when machines would get "wiser" than their creators. But long before that a dog in Pavlov's "tower of silence", where he studied conditioned reflexes, learned to recognize a certain tune regardless of the key it was played in. Another dog was taught to distinguish between a circle and an oval, even a very nearly circular one. The American scientist K. S. Lashley has shown that rats can also be taught "geometry". He placed a rat before a panel with doors on which geometrical figures were drawn. A triangle denoted food behind a door, the other doors led into traps. The rat soon learned to distinguish triangles of different sizes and colours from other figures, as well as from "upside-down" triangles. It thus appears that animal brains can also form abstract notions to some extent. True, animals, like human beings, display varying degrees of "intelligence". Several laboratories in Moscow and Leningrad are currently engaged in a comparative

study of the physiology of higher nervous activity in different organisms.

The results of these investigations are highly interesting. They demonstrate vividly how, with the development of the cerebral hemispheres and the growing complexity of the brain's auditory, visual and other sensory centres, simple sensations gradually evolved into more complex manifestations of reality, a concrete perception of events, a more generalized conception of objects and events and, finally, into abstract thinking.

Rudimentary perception is found in the lowest animals.

Amebas and other protozoans which hardly deserve the name of "animal", are sensitive to a variety of stimuli. They respond to touch, electric shock and acids. They even possess the rudiments of what physiologists call "acquired responses", a minimal ability to "learn", although they have essentially no nervous system, to say nothing of sensory organs or "intelligence". Irritations act on the whole surface of an ameba's body, various parts responding differently to different kinds of stimuli.

Actinial from the Barents Sea and Black Sea display various degrees of sensitivity to temperature and salinity. This is hardly surprising, as the Black Sea is warmer and saltier and the two species of actinial are adapted to their respective environments. But when representatives of each species were moved from one sea to the other they quickly adjusted themselves to the new living conditions.

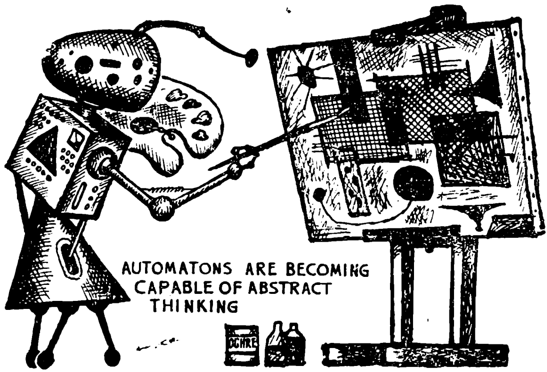
Conditioned reflexes are regarded as the basic criterion of an animal's "abilities". Many attempts were made to develop reflexes in starfish and hydras. When fresh water was poured on a starfish

making its way up the wall of an acquarium it, being a sea-dweller, beat a hasty retreat. After many repetitions the starfish finally "realized" that it was no use trying to reach the top. It settled on the bottom and remained there. Had it developed a reflex of some sort to fresh water? The answer is, no. Forty or fifty minutes later it resumed its attempts to climb up the wall, and renewed fresh-water douches were required to discourage it. The starfish had learned nothing from the previous experience.

Going up the evolutionary ladder, conditioned reflexes, very weak to be sure, have been developed in crayfish. Bees, too, are receptive to some degree of training and can be made to fly towards a specific smell or coloured pieces of cloth. Animals with rigid inborn "programmes" can acquire some minimal experience. On a windy day a spider will spin its web differently than on a calm one. It does make a certain effort to adapt itself to a changing environment.

Such adaptibility is dominant in the behaviour of vertebrates. They easily develop conditioned reflexes in response to diverse stimuli, though the conditioned-reflex activity of, say, a fish and a monkey can hardly be compared.

The quality of an animal's reflexes is not, of course, measured by its responses to such simple stimuli as a bell, light or even a tune. Animals are not merely shown objects, but they must distinguish between similar objects of different colour or shape. They must learn the specific objects which signify a reward food. Such experiments are used to study the rudiments of elementary thinking processes. The animals must analyse a situation and determine the important features, that is, they must generalize their visual,



auditory and other sensations. One should not be surprised at an animal's ability for such complex forms of cerebral activity. The essential thing is the extent to which it is capable of generalizing and analysing its impresions.

Man and animals, Engels wrote, share all types of mental activity in common: *induction*, *deduction*, and hence *abstraction*, *analysis* of unfamiliar objects, synthesis, and, as a combination of the last two, *experiment*. All these methods are essentially the same in man and in the higher animals. They differ only in degree.

Observations show that even fishes, turtles and chickens are capable of simple forms of analysis and synthesis (rudimentary forms of abstraction and generalization). Rats stand a little higher. The ability for synthesis is much more pronounced in the lower monkeys than in dogs, and in the apes it is highest of all. The elements of thinking ability which apes possess represent a transitional stage to the real intelligence and conscious activity of man.

We see that before saying whether machines could be made to "learn" researchers had to decide whether animals could learn. In doing this they also largely answered another question: do animals think? We now know that when we speak of animal "intelligence" we mean not real mental activity but a more or less complex pattern of conditioned reflexes.

Up till now we have mentioned only the simplest type of reflex action, such, for example, as when a light stimulates the "digestion centre" of a dog's brain. Life, of course, is much more complex.

A man throws a bone out of the window and a dog runs out of the room, down a flight of stairs, around the house and into the back yard—all this without ever having been taught in any way to fetch bones from the yard. Seeing the bone thrown into the yard, the dog must "draw up a plan" of how to get it. This brings a whole chain of reflexes into action. There is the door from the room, which is associated with an oft repeated action—and the dog pushes it open and finds itself on the staircase landing. The sight of the stairs suggests the way down. In the yard the smell of the bone guides the dog to its goal. Thus unfolds a chain of reflexes triggered by the most powerful stimulus of the moment, in our case the sight of a bone thrown into the yard. The dog knows the yard, and its "image" is projected into the dog's brain by the sight of the falling bone, giving rise to a complex behavioural pattern.

At the Pavlov institute even more complex systems of interrelated reflexes were developed in various animals. The apes Rosa and Rafael would erect pyramids of boxes, punt a raft across a pond or open a door with a key to get at

a titbit. Such "intelligent" behaviour of animals is at least as remarkable as the abilities of "thinking" machines. But why should it appear remarkable? Life daily confronts animals with new situations calling for adaptive responses. They must learn to avoid situations involving danger or pain and exploit those that yield food. Animals quickly take their bearings in a new environment and adapt themselves to changing conditions by developing new patterns of behaviour. In other words, the animal's brain is continuously constructing new programmes of action.

This is how the higher animals behave, which, as well as having inborn unconditioned reflexes, are able to acquire a wide range of temporary, conditioned reflexes. In developing cybernetic systems the scientists sought to go over from "insect" machines, operating according to the rigid patterns of unconditioned reflexes, to "vertebrate" machines capable of appraising a situation and drawing up a suitable programme. Each such machine should be able to acquire its own individual experience just as two cubs from the same brood will develop different patterns of behaviour if one is brought up in the forest and the other in the open steppe.

Guessing Games for the Brain

"Sultan, food!"

The chimpanzee sitting calmly in the corner springs up, grasps a bar of his cage and swings back and forth, ready to take the food offered to him.

The attendant places an orange on a table outside the cage. The ape leaps to the bars of the cage

and pushes his arm through. But the orange is too far away and he can only reach the ends of several strings arranged on the table. The orange is tied to one of the strings. Momentarily baffled, the ape lumbers away, casting a disconsolate glance over his shoulder at the fruit. It seems such a pity to leave an orange like that. Impossible, in fact, and Sultan reaches out again for the table. His hand slides over the top and he pulls at the strings. Finally he gathers them in his fist, draws them in and triumphantly makes away with the orange. The experimenter, however, is dissatisfied.

"Too many movements and too much time wasted", she says looking at the clock. "Let's have another try."

This time Sultan pulls one string at a time until he gets to the one with the prize tied to it.

"That's better," the experimenter remarks to herself as she looks at the clock again.

I witnessed this scene at the cybernetics laboratory of Professor Samuel Briness. But why, you might ask, are cyberneticians wasting their time on training animals?

As we know, animal behaviour is a pattern of interrelated reflexes. Hitherto scientists analysing animal behaviour had restricted themselves to breaking down the long and frequently branching reflex chains into simpler links. Professor Briness and his associates were the first to view experiments with "intelligently" acting animals through the eyes of a cybernetician.

Would it not be possible, they thought, to deduce the rules according to which a reflex chain is constructed in a dog's or ape's brain? This would provide the key to an understanding of

how living organisms develop their "operational programmes".

The initial task was simple enough: to trace the manner in which the living brain perfects an existing programme. When an ape is first confronted with the problem of reaching for fruit lying on an awkwardly standing table a good half of its motions are quite useless and do not contribute to the achievement of its goal. The animal still has no idea as to what motions are necessary and what are useless.

A dry record of the experiments, in which the ape's antics and contortions are set down in suitable symbols, reveals how the living brain handles the problem with which it is confronted. Various movements are discarded one by one on a trial-and-error basis. If the omission of a motion does not prevent the animal from getting the food, the unnecessary link in the sequence of actions drops out. If a movement essential for achieving the goal has been omitted in a trial, the movement is restored. All the links in the new reflex chain are tested until the useless movements are discarded. At the first try it took Sultan 80 seconds to get the orange. Ultimately he cut the time down to two seconds.

Only advanced animals with considerable memory capacity, like dogs and primates, are capable of such self-improvement. The mechanism is poorly developed in a rat's brain and nonexistent in a pigeon's.

This primary physiological mechanism helps the brain to select those elements of the programme which best agree with external conditions. As a result a multitude of random, purposeless motions is cut down to a few purposefull actions which emerge as "intelligent" behaviour.

This is how an existing programme is improved. But how does it develop in the first place? Physiologists undertook to trace the hidden mechanism. The part of "environment" was played by the experimenter, who drew up an artificial pattern of behaviour. Schematically it was recorded as: "Bell—jump on stool—buzzer—press pedal—food." The test dog, naturally, was ignorant of the scheme, just as in life a young animal does not know what responses to external stimuli can result in a hearty meal. In both cases it must guess what action will yield food.

"It is something like a parlour guessing game," Professor Briness explained. "One person leaves the room while the others draw up a pattern of actions which he must guess. For example he must go to the window, close it, take a flower pot from the sill and put it on the table. Tom, Dick or Victor enters the room and starts moving randomly from table to wardrobe, from wardrobe to door. Whenever he makes a step in the right direction the others prompt him with cries of 'Warm, warmer, hot!' Thus he gradually guesses the pattern of behaviour required of him. Similarly, our test animals 'guess' the behavioural patterns we devise for them."

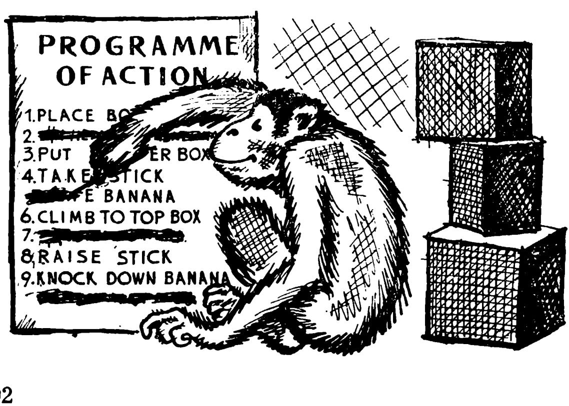
The scheme cited above indicates that the dog will be fed only if it jumps on a stool when the bell rings and then presses a pedal when the buzzer sounds. The dog begins by going through a great number of random motions until it chances on the required one and jumps on the stool. A reward of food makes it remember the action, and when it wants to eat it jumps straight on to the stool. If the food reward is occasionally omitted the dog takes note of other phenomena accompanying the reward. Thus it discovers that food

comes only together with a bell, and it jumps onto the stool as soon as the bell rings.

Again the reward is withheld, and the dog goes through a series of random motions, as if looking for the right one. It happens to press the pedal, and is rewarded with food. When this has sunk in the reward begins to come only with the buzzer. Thus the dog gradually learns to follow the sequence planned by the experimenter. One could say that it has learned the laws governing the environment and how to use them to get food. In other words, the living brain has produced a programme of action best adapted to the new circumstances of the environment.

In real life animals develop much more complex reflex patterns made up of many chains analogous to the one described. How does the brain cope with all this?

Bells of different pitch rang again in the laboratory, metronomes clicked and coloured lights flickered. The brain was forced to make its way through a maze of ingenious traps set to unravel the mystery of its logical behaviour. Life was made more and more complicated for the animals.



Thus, a blue light would go on during the experiment, and no amount of stool-jumping or pedal-pressing would yield food: the reward followed only if there was no blue light. After a few tries the dog discovered the connection between this new stimulus and the previous conditioned signals and responded only when the blue light was off. The blue light acted as an inhibitor of the whole chain of conditioned reflexes—which is why this kind of negative stimulus is called a conditioned inhibitor.

It was observed that if the conditioned inhibitors were switched off after some specific motion the animal would start repeating it over and over again. The brain apparently regarded this motion as being responsible for removing the inhibitor and acted accordingly. This observation was used to complicate the reflex chain still more. To the basic "food" reflex chain there was added a "side" chain, also consisting of two or three links. This side chain of reflexes was brought into action to remove the conditioned inhibitor, the blue light. A pattern of branching reflexes was thus developed in the brain.

Experiments show that the brain is quick at forming new reflex chains; they rapidly develop and extend like a chain reaction or avalanche. The development of a new link or even a whole sequence no longer requires reinforcement at every stage. As the links add on they dovetail, as it were, one to the other. Only a general final reinforcement with food is necessary. The "chain reaction" of reflexes accelerates the development of new reflexes and new action programmes.

This ability of the nervous system opens up boundless opportunities for making reflexes more and more complicated. A conditioned inhibition

is developed for a side reflex chain. Using it as a reinforcement, it is possible to add another branch to the side chain, and so on without end. This was demonstrated especially vividly when experiments were extended from animals to people.

Switches and Controllers

Anatoly Napalkov, a young physiologist, was the master mind behind a series of new experiments carried out at Moscow University. When I first came to interview him he had just returned from an international congress on cybernetics in Amsterdam. He was brimming with impressions of his meetings, discussions and arguments with scientists from many countries.

"Many interesting investigations were reported," Napalkov said. "Cybernetics is penetrating deeper and deeper into physiology."

What attracts the investigators of living organisms to cybernetics? Why is cybernetics so indispensable to explorers of the living brain? After all, scientists were seeking the answers to the secret of man's intelligent behaviour and animals' purposeful behaviour long before the word cybernetics was coined.

Edward Thorndike, for example, founder of one of the schools of psychophysiology, finds that initial animal behaviour is chaotic and random, most motor actions are purposeless. These are gradually discarded until only the necessary movements remain. Animals thus develop strictly purposeful behaviour through experiment, through trial and error.

Other scholars say that not all animals behave so primitively. An ape, for example, will not hes-

itate to arm itself with a stick to get hold of a choice morsel that lies out of reach. It manipulates the stick purposefully, and if it cannot achieve its goal it does not wander about aimlessly but devises some other method, like stacking up several crates and boxes to reach the food. It is sometimes possible to trace the development of a correct "line of action". After an unsuccessful attempt the ape may sit down as if to ponder over what to do next. The impression, according to this school, is that an image of the necessary mode of action forms in the animal's brain, and it acts accordingly.

Both schools are right in their different ways, but their approach, Anatoly Napalkov says, is too narrow. There can be no doubt that animals act by trial and error as well as on the basis of specific images or mental analogues of the external world. The brain's functions, however, cannot be reduced to either the one mode or the other. It is much more versatile. The higher an organism stands on the evolutionary ladder the more complex and precise its cerebral processes. They cannot be studied by investigating particular modes of cerebral activity or the functioning of individual nerve cells. What is required is a method which can provide an insight into how complex ensembles of many neurons function. It is a question not of physiological but of mental processes, that is, of the laws according to which the brain handles and processes incoming information. This is where cybernetics comes in handy.

In analysing cybernetic systems from this point of view one cares little for the laws governing the flow of electric current through electronic hardware. Similarly, in analysing cerebral activity one can forget for the time being physio-

logical considerations like the propagation of stimulations or inhibitions among nerve cells. Of primary interest are the rules, or algorithms, as they are called, according to which the brain processes information.

Neurocyberneticians suggest that the brain employs a hierarchy of algorithms of varying degrees of complexity. Every higher-level programme forms lower-lying programmes. The lowest-level programme essentially comprises the simplest behavioural patterns of animals, the rules for developing reflexes. The second-level programme develops rules according to which new forms of purposeful behaviour may evolve. The third level develops the algorithms of self-learning. Only man possesses this level. That is why a thorough investigation of the functioning of the brain as a cybernetic system requires experiments on human beings as well as on animals.

Soviet scientists are giving much attention to the study of the algorithms employed by living organisms. They began by analysing the rules according to which learning takes place. It is similarly possible to study any complex patterns of behaviour, such as the manner in which generalized concepts are formed and problems are solved.

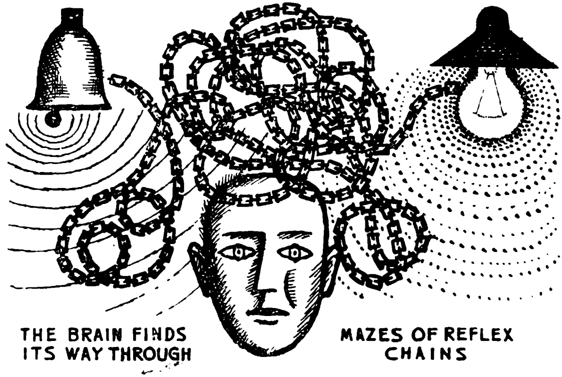
An algorithm is essentially a set of fairly simple rules. Their simplicity usually misleads the uninitiated. "How can one acquire experience and solve problems with the help of such simple rules?" people often ask. But this is hardly surprising. Take mathematics. If you are not very familiar with the subject it is impossible to follow the reasoning of a person solving a difficult problem. He strings out rows of numbers, puts them in

brackets, separates them by lines and erects columns of figures. But if he describes the rules of division, multiplication and so on stage by stage the problem no longer appears formidable. These mathematical rules constitute the algorithm for solving the problem.

Physiologists proceed in essentially the same way. The main difference is that the rules of arithmetic are free creations of the human mind, and if one knows them one has no difficulty in describing them. The rules according to which the living brain functions were drawn up by nature and are unknown to man. The task is to understand them.

Not all cyberneticians take such an approach to brain research. Many of them, including such lights as McCulloch, Pitts and Kleene, hold that the first thing to do is to study the internal structure of the brain, the principles of neuron geography and interconnection. Knowledge of this kind, they say, will provide an insight into how the brain operates. There is no doubting the value and importance of a physiological study of the brain. Nevertheless, Anatoly Napalkov points out, it may well prove more effective to elucidate first of all the algorithms according to which the brain works, reduce them to separate precisely formulated rules, and then construct models of nerve pathways which would operate according to those algorithms.

If artificial nerve pathways built into an electronic machine fail to ensure learning it means that something is wrong either with the rules of operation or with the nerve circuits. In either case it would be necessary to resume experiments with living organisms in order to check earlier conclusions. By going over from man to machine



and back to man the scientists hope to get to the truth much quicker.

The laboratory for experiments designed to bring to light the complex algorithms followed by living systems is much the same as the conventional laboratories in which conditioned reflexes are studied, with the same set-up of conditioning frames, lamps, bells and other simple devices. There are conditioning frames for rats, dogs and human subjects. In response to various stimuli the test animals must press a pedal, jump on to a horizontal bar or perform some other simple actions. The same principles are used in the study of animals and human beings. The investigators develop complex reflex patterns and observe the rules according to which the brain sets them up. After that they determine how good the various algorithms are in different circumstances. At this stage their investigations are largely restricted to primitive information patterns. They have departed from purely physiological problems but have not yet invaded the domain of psychology.

Nevertheless, experiments on human subjects differ markedly from experiments on animals. The human brain is not satisfied with the role of an unreasoning "computer" which merely responds to sundry signals. Animals usually wait passively for the appearance of a signal. Human subjects take part in producing new signals by manipulating various switches and buttons. Such "reconnoitering" of the situation facilitates the formation of reflexes.

It was found, among other things, that besides the "triggering" conditioned stimuli described by Professor Anokhin there also exist "switch-on" stimuli, which do not elicit specific responses but affect the nature of a person's responses to the "trigger" stimuli. Reflex signals of different kinds comprise a definite order with strict subordination of lower to higher stimuli. A stimulus of the highest order will switch on a whole pattern of previously established reflexes. Other stimuli switch on individual reflex chains within the overall pattern; yet others switch on the side branches of various chains. An inferior switch-on signal will have an effect only if a superior signal has been effective. This means that activation of a complex programme requires the simultaneous presence of two or three switch-on stimuli in addition to the primary thirst, hunger or other urge.

The brain has shown itself to be very flexible in operation. This was revealed in a series of experiments in the course of which the initial stimuli of conditioned responses were varied in an attempt to confuse the brain. The experiments showed that when it is confronted with a change in conditioned stimuli the brain initially attempts to make use of old reflex chains which have previously proved their worth in solving problems.

Only if they do not stand up to the test does it proceed to draw up a new programme of operation.

These experiments demonstrated that those reflex chains are most active which have led to success in the solution of earlier problems. The brain resorts to them in the first place, and only if they fail does it undertake to frame a new programme of operation.

"Our experiments and observations," Anatoly Napalkov told me, "have given us a comprehensive picture of the way in which the brain screens and processes information in a changing environment. They have also confirmed the correctness of our method. Only by studying the interconnections between an organism and its environment can one gain an idea of the rules according to which incoming information is processed by the brain."

Many such rules have been studied and described by physiologists working in the laboratories of Moscow University. They found, for example, that the human brain reacts very quickly to new signals. If a hitherto unused signal is introduced in the course of an experiment the brain tests it to see whether it can help achieve the required goal. Certain rules which the brain follows in such cases have already been established.

An analysis of the processes by which new programmes are formed has revealed some interesting points. Intermediate objectives in the search for a new programme of behaviour, it was found, are achieved by the development of temporary conditioned reflex patterns. Subsequently they are inhibited but they do not disappear completely. In solving a new problem the brain makes use of already available patterns of reasoning. The development of such subprogrammes is of great impor-

tance and thanks to them the brain does not have to start each time from scratch.

It is impossible and unnecessary to list all of the brain's operational algorithms. The important thing is that the laws which the investigators have so far uncovered offer an insight not only into rigidly logical mental processes but also into such intangible manifestations of cerebral activity as intuition and the well-known feeling of having "almost got it."

Man has a natural urge to acquire information and increase his body of knowledge, but of equal importance to him is protection against superfluous information. The importance of this was driven home when engineers proceeded to construct a machine capable of independently achieving a goal set by its designers, a machine capable of learning from its own experience. If it simply memorized all incoming information its memory store would soon be filled to capacity and no room could be left for really pertinent information. In seeking ways and means of shielding the machine from unnecessary information the scientists again turned to the brain, with its ability to learn without being overwhelmed by the endless stream of information coming into it.

Two basic rules were thought to be essential. The brain memorizes a connection between stimuli only if they repeatedly coincide in time, indicating the existence of some underlying law or regularity. In this way the brain determines whether a message is important or not. It must also establish which of the discovered laws are useful. With animals this is easily done: they memorize only such information as leads to food or the satisfaction of other vital requirements.

The problem would thus appear to be a simple one. Both rules must be incorporated in a machine that would learn by trial and error. Actually, though, it is not quite so simple. To be sure, the machine would not memorize useless things, but much valuable information would also slip from its memory. Generally speaking, it would memorize only those correlations between isolated facts that lead directly to "food", i.e., the achievement of a set goal. But the road to a goal is not necessarily straight. The brain may choose a "roundabout way" and succeed where a "straightforward" machine would fail. After several attempts to go ahead at a point where the correct "road" branches the machine would decide that the objective is unattainable and, lacking the brain's inventiveness, would let it go at that. Thus, the principles for selecting information mentioned before are inadequate.

"Physiologists had hitherto overlooked the mechanisms that protect the brain from too much information," Anatoly Napalkov said. "We began to search for the extremely flexible and precise methods of data selection which we know must exist."

The investigators soon found that new criteria for screening useful information are utilized when new programmes are being developed. There are control mechanisms that only detect the useful signals and point them out to others, which then decide which signals are the more important. The more a reflex chain branches the greater the number of control mechanisms screening the useful information.

"We call them 'recruiting agents'," Napalkov said with a smile. "They are not just passive observers. Every signal 'recruited' by them in turn

starts to recruit new signals. Thus, as learning progresses the brain's ability to acquire useful information increases."

This, however, is not enough. The road to an objective may be so involved that each individual stage offers no more than some general hint towards a successful action in the future. What is the criterion of usefulness in this case? The investigators found that some of the control mechanisms possess "extraordinary powers". They select information at their own discretion, without seeking specific confirmation of its usefulness or otherwise.

This seemed to clarify matters, but as soon as the experiments were transferred from animals to the selective mechanisms of man discrepancies arose.

"The results were quite surprising," Anatoly Napalkov relates. "In man, reflex circuits form very quickly without having to be reinforced by a 'reward'. It would thus appear that the human brain memorizes new information which has not been screened by the control mechanisms or reinforced by 'food', as if man did not have to be protected against redundant information."

Further experiments showed that this was not so. Simply the protection system proved to be more complex and flexible than originally supposed. The study of these highly perfect mechanisms has only just begun.

"Surprisingly," Napalkov added, "not all actions of the protective mechanisms are to our own advantage. We spend years studying a foreign language or some other school subject not because we couldn't have memorized everything at once but because of the special mechanisms that actively oppose memorization.

"At one time they helped our forebears to grasp what really mattered without wasting their memories on all they saw. Today we hardly require so severe a protection system. Irrelevant information can be consciously barred from the brain, and as often as not nature's protective mechanisms are more of a hindrance to us.

"At times our nervous system appears to be acting to its own detriment, or at least contrary to the organism's best interests at a given moment. Take an illness like hypertension. Increased blood pressure in a moment of danger, when all the organism's reserves must be instantly mobilized, is undoubtedly useful. It ensures maximum energy output. But when high blood pressure persists without any apparent cause it turns into an illness. It is clearly due to some malfunctioning in the blood pressure control system. At the same time, attempts to cause hypertension artificially, by tampering with the inborn mechanisms controlling blood pressure, have failed. The disorders, it appears, lie at a 'higher' level."

Napalkov and his associates assumed that the fault lay not in the automatic regulator itself but in the control algorithms of the second, and possibly the third, order. This is a case when our nervous system's ability to build up rapidly new reflex chains turns to its disadvantage. Nerve pathways which had once triggered a rapid increase in blood pressure become permanent features of the nervous system, and indeed expand. As a result, an inordinately high blood pressure is maintained to the detriment of the organism. That this is so was confirmed experimentally. Dogs were given electric shocks accompanied by a bell. The next day the bell alone caused a slight rise in blood pressure. The dogs

were then subjected to the bell stimulus for several days in succession, and they developed hypertension, their blood pressure rising from 130 mm to 250 mm of the mercury column in ten days, which persisted for eighteen months.

The explanation is that a signal which had coincided with an unpleasant stimulus only once was incorporated in the algorithms responsible for blood pressure regulation, something which should not happen in a well-functioning nervous system. The rule of repetitive association of several stimuli had been violated, to the detriment of the algorithms responsible for the usefulness of the animals' reactions. Most important, the dogs were cured not with drugs but by so to say rectifying the nervous system's functional algorithms.

The case described involved the controls governing our internal organs. Does something similar take place in the mental activity of the brain?

It is sometimes easier to trace the general laws governing the operation of a mechanism when the mechanism breaks down. A fault may bring to light interrelationships between different parts which cannot be detected in a smoothly running machine. This is why physiologists study not only smoothly operating nervous systems but also malfunctioning systems in which the "operational programmes" have been drawn up incorrectly.

A Vicious Circle

Messages of all kinds flow to the brain in an endless stream from the body's receptors. As Pavlov put it, the brain is like a vast control board with countless lights flickering on and off in response

to the signals coming in from the outside world. The importance of this continuous contact between the brain and the environment had originally been grossly underestimated. Then one day the Canadian psychologist D. O. Hebb staged an experiment in which several healthy young volunteers were isolated in small, dark, sound-proof, air-conditioned chambers. Tactile sensations were removed as far as possible with the help of gloves and cardboard tubes on their arms. The young men spent from thirty-six hours to ten days in complete isolation from any kind of information. The result was remarkable. The brain could not stand the isolation and the men were harassed by hallucinations and delirious visions. This case was described by Paul de Kruif in his excellent book, *A Man Against Insanity.*

That the brain is in constant need of a continuous flow of information has been confirmed by the findings of the new science of space physiology. Investigations carried out in sound-proof chambers have revealed that the brain, far from prospering in absolute silence, cannot function normally without some background noise. Visual, tactile and temperature sensations are also essential. A prolonged absence of messages from any one of the many constant sources of information affects the harmonious functioning of the brain's 14,000 million nerve cells, and nervous disorders may develop. A man may be beset by obsessive memories or fixed ideas and hallucinations may arise. At the same time he will eat and sleep well and be able to solve arithmetical problems. His brain is not affected by a disease, yet it suffers from the effects of forced inaction.

The picture of psychic disorders is so complex that workers find it impossible to agree on the

causes of many disorders of the brain. In his book Paul de Kruif describes another interesting case. In one Swiss laboratory a Dr. A. Hoffmann accidentally sucked in through a pipette several drops of a liquid containing ergot, a fungus that grows on rye and wheat. Before the hour was out his mind began to waver and his speech became incoherent. When one of the laboratory workers entered the room he found Hoffmann crouched in a corner and staring with terror at this desk. The doctor had gone mad.

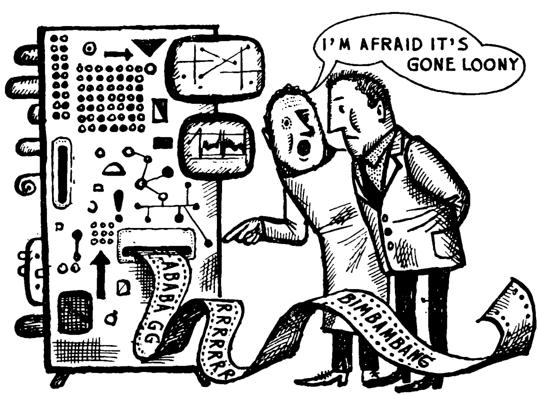
In several days the disease began to recede, and soon Hoffmann recuperated completely. The lesson of his temporary insanity, however, was not lost upon him. It had quite apparently been caused by the ergot, which had intoxicated his brain. Hoffmann then deliberately swallowed several drops of ergot—with the same effects. He thus proved that insanity could be caused artificially. An infinitesimal amount of ergot (one-seven hundred millionth of a man's weight) can mentally incapacitate a healthy young man for five to ten hours. The experiment offered graphic proof that psychic disorders could be caused by chemical intoxication of the brain. Today more than 15 such substances are known.

Workers of the Institute of Psychiatry showed me dogs after intravenous injections of a drug causing psychic disorders. The animals were standing in their cages in the most incongruous postures, as if they had been placed under a spell by some evil genie. One dog had its head cocked in the most absurd fashion, another was balancing itself with difficulty on widespread legs. They seemed petrified. People suffering from many kinds of mental disorders frequently fall into such petrified states resembling spasmodic convulsions.

In another room a monkey was lying in its cage. Suddenly it raised its head, stared intensely at a blank wall as though listening to something and retreated into a corner in evident fright. It too had been given one of the drugs.

It should be said that in these experiments scientists were faced with something of a dilemma. It is fairly simple to study the syndrome of, say, influenza in dogs. But how can one use animals to investigate mental disorders which affect the higher thinking functions of the brain peculiar to man alone? In animals one can reproduce only certain symptoms of mental diseases, very simple in rats and dogs, somewhat more complex in monkeys and apes. That these symptoms follow the administration of specific chemical substances supports the idea that many psychic disorders start with intoxication of the nervous system. What happens after that?

One day a fault developed in an electronic computer. Instead of carrying out its assignment it endlessly repeated an operational cycle and



could not go over to the next stage of calculation. In short, it acted as if it had "lost its senses". This experience led someone to hypothesize that something similar takes place in a human brain suffering from chemical intoxication. Certain drugs evidently interfere with nerve impulses in the brain and make them go about in circles.

Normally a person cannot concentrate his attention on one object for very long. The development of the aforementioned repetitious state forces the attention to concentrate morbidly on a single idea, giving rise to persecution mania, megalomania or other such disorders. Some recollections may recur endlessly, pushing all other thoughts out of the mind—and a person is haunted by a fixed idea.

A cybernetician would say that a mental disease is caused by a malfunctioning in the brain's information processing and storage system. As a result many of the brain's neurons are engaged in an endless recycling of useless nerve impulses. The reduced ranks of unaffected neurons are unable to cope with all the functions of the brain. Incidental information, which is normally sifted away, may now get firmly imprinted in the memory and serve as a source of more false conceptions. Nonexistent images are projected in the brain and hallucinations appear.

Such a cybernetic explanation gives a fairly accurate picture of psychic disorders. Once again machines have come to man's aid. Certain types of faults in computers present some striking analogues of phenomena which occur in a diseased brain; in other words, it is possible to develop analogues of psychic diseases, in whole or in part, and use them to study how the illness develops. Meanwhile, however, the doctors turned

back to their dogs and monkeys: much more has to be learned before diseases can be modelled.

Again dogs were treated with drugs. This time the dosage was much smaller and the symptoms did not develop completely. Some interesting nervous disorders were observed. Thus, a dog lapped broth from a pan but failed to lower its head as the level of the broth fell and was soon lapping at nothing. The food reflex had worked, the brain had issued the necessary commands to the muscles of the tongue and neck, but coordination was lacking. The conclusion is that the disorder primarily affects the higher functions of the organism: it disrupts the precise mechanism of conditioned reflexes and other functions in animals and impairs speech and motor control in man. This was verified in experiments involving some complex reflexes. For example, a dog was rewarded with food only if, following a specific signal, it jumped on a stool. Furthermore, combined stimuli, such as a bell together with a light, were used, with the additional complication that only a white light signified "food". After the reflex was developed to perfection and firmly implanted in the dog's brain a small dose of a drug was administered. Immediately the clear-cut pattern broke down and the conditioned reflexes developed with such trouble disappeared. The dog "forgot" that a white light together with a bell meant "food" and it jumped on the stool when only the light was switched on. It could no longer cope with the more complex situation. Rats which had formerly taken fifteen minutes to find their way through a maze now wandered inside it for many hours.

Despite the relative novelty of these experiments, it is already apparent that in an intoxicated

brain normal reflexes break down and erroneous reflexes take their place. The process is a gradual one, with first one link falling out, then another, and so on until the whole chain disappears. How do the new abnormal, pathological reflexes appear? Can the process be halted and reversed?

The scientists have some answers to these questions. As is known, a conditioned reflex to a light, bell or any other stimulus develops only by reinforcement. If a bell is rung only once during a dog's feeding time, the animal will not pay the slightest attention to it on another occasion. The dog will be right, too, for the brain should not respond to incidental signals not associated with food. Only after several such coincidences does the dog associate a ringing bell with food. In this way the brain protects itself from irrelevant associations. Only verified information reaches the brain, and thanks to this reflexes are reflections of the real environment.

That is in a healthy brain, but what happens when the nervous system is out of order? Experiments show that when an animal is traumatized, as by a severe fright, the brain loses its vigilance and reflexes may develop immediately in response to irrelevant signals. This means that the way to the brain is open for all kinds of information, whether useful or not. It rapidly fills the memory to capacity leaving no place for useful messages. The brain forms an erroneous image of the environment.

Something analogous may prove true of psychic disorders in man. It may well be that the control system responsible for screening incoming information breaks down and the brain is swamped by a torrent of unverified messages as a result of which pathological reflexes develop. The

process may well result in nerve impulses running after each other in circles, which many workers regard as the cause of such brain malfunctionings.

This, however, is but one of a number of possible mechanisms giving rise to hallucinations. Pathological reflexes need not necessarily develop on the basis of an incorrect selection of incoming information. Cybernetically speaking, the matter need not necessarily be one of incorrect information processing: it might be a question of storage as well.

A sequence of reflex motions, rewarded by food, was developed in a dog: on hearing a bell and seeing a light it jumped on to a table and back to the floor, pressed a pedal with its paw and jumped on to a stool. When the dog was not hungry it did not respond to the conditioned stimuli. It was then fed a very salty broth, and thirst took the place of hunger. Now it responded to the stimuli again, even though they denoted food. The thirsty dog's brain was incapable of a sober analysis of the signals and the dog went through the whole sequence of food reflex responses even though they held no promise of water. As a result the dog developed a drink reflex chain containing elements of old reflex associations.

It is suggested that in this way shreds of old recollections and associations give rise to the distorted, hallucinatory impressions of reality that arise in the brain of mentally deranged people. This, of course, is a very rough and approximate picture of the processes which take place in a malfunctioning brain. It can be made more precise with the help of electronic "insanity analogues".

How to Teach a Machine

The main purpose of the experiments with healthy and afflicted animals, you will recall, was to establish the rules according to which the central nervous system functions. Which of the algorithms discovered in these investigations have proved useful for learning machines?

"One could expect," says Anatoly Napalkov, "that each form of behaviour would correspond to a specific programme, to a specific reflex chain triggered by the relevant conditioned stimuli. In this case every conditioned stimulus must elicit a specific response in the nervous system, meaning that a great number of independent reflex circuits would have to exist—defensive, food, etc. If this were so, the ability to develop new reflexes would depend directly on memory capacity, insofar as the memory of every conditioned stimulus must be stored in a separate unit.

"However, a control system of this kind would be cumbersome in operation. A new programme could be developed or an old one modified to suit changes in the environment only after the removal of earlier reflex circuits, which would thereby free the memory store for new reflexes."

But, Napalkov says, there are other ways of handling the problem. The control system need not have ready-made programmes for every possible contingency. The memory carries a minimum of information, which can be used to build up a number of programmes. Stored information can be said to be generally available to the neuron population at large. The brain uses some specific data to set up a reflex chain. Afterwards it returns this data to the store for subsequent use. Information is stored in the

brain without interfering with the other functions. When new messages enter the brain, are processed and a specific programme develops, relevant requests are sent up to the cerebral "archives" for the required information.

Normally a person or an animal will not respond without need to the conditioned stimuli of a reflex pattern. Only when a person is given some specific task, or when an animal experiences thirst, hunger or some other urge does a specific "food", "thirst", "light" or "bell" reflex circuit go into operation. Such a control system possesses much more flexibility, the nervous system can rapidly adjust itself to changes in the environment, and its memory capacity can be smaller. This is of tremendous importance. The brain has no separate "memory unit" and it is probably the selfsame nerve cells responsible for logical action that act as memory storage units. Consequently, the greater the number of free cells, the more diversified and productive the brain's work can become.

A control system of this kind, however, must possess some supplementary units to provide for the extraction of requisite data from the memory at short notice. In this case the possibility of developing new behaviour patterns depends not so much on memory capacity as on the perfection of the supplementary mechanisms. The experiments described earlier confirm that the nervous systems of animals and man function according to the second pattern.

In the first place, there must exist a special physiological mechanism which reviews the information in the memory store and compares it with incoming information. Thanks to this mechanism the brain does not have to scan all the

stored information from the beginning in search of data required for a specific purpose. It carries out a selective search. This is something like finding a book in the library according to its card number. The librarian walks along the shelves with the reader's request. When the numbers on the request card and the back of the book coincide the librarian takes the volume from the shelf.

In an animal's brain the role of "librarian" is played by a nerve stimulus. The stimulus spreads from some neuron ensemble, the thirst centre for example, along previously formed nerve pathways. The search for required information is specifically orientated. The first to be excited are the nerve pathways arising within the centre. One by one the links of the old reflex chains are activated, until the goal is achieved and the animal has quenched its thirst.

If two different reflex chains, say "thirst urge" and "hunger urge", have a common stimulus, the nerve excitation, as we have seen, may spread to both.

The information carried in old reflex chains is continuously compared with incoming signals. The scanning continues until the stored and incoming signals coincide, the "book" is taken off the shelf and delivered to the "reader".

The scanning of this or that chain begins only if the relevant "switching-on" stimuli are present. This makes the process of scanning of previously accumulated information dependent on specific external conditions and keeps the brain from being diverted by irrelevant stimuli. The environment abounds in stimuli, and if the brain reacted to them all a person's behaviour would be quite disjointed. Thanks to the system of screening irrelevant signals selective search is strictly

purposeful. The brain does not scan all the information in its memory stores but only a small and relevant portion of it. It engages in the "step search" mentioned earlier, and its "steps" are normally in the right direction.

Selective search is characteristic of cerebral activity in higher animals only. This highly perfect mechanism has been found in dogs. It is barely traceable in birds and totally absent in turtles. Rats, like modern electronic machines, simply scan all the information stored away in their memories.

Why is a reflex triggered only when the "book" and "request" numbers coincide, that is, when two waves of excitation are superimposed? Apparently some of the brain's nerve cells are "double-barrelled", as it were, and fire only when stimulated by a double dose of nerve impulses.

Thus, the algorithms which enable the brain to develop new and complex operational procedures most economically, without going through the whole body of information in its memory store, must be based on two requirements. On the one hand, the scanning or search procedure must be selective and purposeful. On the other hand, it must be in strict accord with specific external conditions. Both requirements are effectuated by the peculiar physiological mechanism based on "double-barrelled" nerve cells.

To uncover the rules according to which the brain programmes its work was only half the job. The next step was to incorporate them in an electronic machine.

The first learning machine was not a very complex device. The size of a small cabinet, it had only a hundred electron tubes. Its console was studded with rows of coloured buttons and sig-

nal lights. By pressing various buttons the experimenter simulated a bell, buzzer or other conditioned stimulus to which the machine had to respond by flashing on various lamps.

The "untrained" machine behaves as erratically as an untrained puppy. It is governed by a random-action unit which switches on the lights at random. Then one action is reinforced with "food" by pressing an appropriate button. The random-action unit is cut out of the circuit and the machine "memorizes" the "food"-reinforced stimulus.

"Memorization" is effected by "central" electron tubes which are activated only when current comes in simultaneously through three input leads. These tubes act like the switching neurons mentioned before. Along one lead comes the stimulus from the "ear" (the button which simulates a bell). Along the other comes the excitation from one of the coloured lights symbolizing the machine's response. Along the third lead comes the "food" reinforcement signal. The machine does not have a separate memory unit. The "memory" electron tubes are incorporated in the logic unit. This is very much like the living brain.

The machine simulates only a single reflex action and in this respect it is not much "cleverer" than the electronic tortoise which moves towards light. In order to enable the machine to choose between several external stimuli the central tubes were joined together. Now the machine could develop different responses to a "bell", a "buzzer", or a "light" and was ready for the crucial learning test, the development of a branching reflex chain.

Inhibition of old reflexes is also important. For this, the button denoting "bell" is pressed and the machine's response (the flashing on of a red light) is not reinforced with "food". This is repeated

several times and, like dogs in similar experiments, the machine reverts to random actions and the lights on the console flicker irregularly. This is effected by a counting device which switches on the random-action unit when responses are not reinforced. The machine has "unlearned" and is ready to tackle a new task.

It is a fascinating sight, and one can watch the machine for hours on end as it simulates the behaviour of a trained dog with the highest canine intelligence (though the first learning machine's IQ was nearer that of a pigeon or a rabbit).

This machine simulating the hidden programmes according to which the brain forms conditioned reflexes was constructed by engineer V. Svechinsky according to a scheme developed by Samuel Briness and Anatoly Napalkov. So far it performs no greater a task than the flickering of lights on and off. But the time will come when learning machines will be put to work in many industries. One plan is to use a learning machine to get down to the bottom of the processes involved in the manufacture of synthetic rubber. Such a machine would respond to temperature, pressure and chemical composition "stimuli". The reinforcement stimulus denoting a correct response would be given by the quality and quantity of the finished product. It is hard to say how such a machine will cope with its duties, for it will have to engage in virtual research work and engineers will not always be able to guide it. In fact, it will be left to the machine to blaze the trail to be followed by the engineers.

Learning machines will undoubtedly find many applications, and not least of all in medicine. An electronic doctor capable of memorizing hundreds of symptoms and diagnoses and, furthermore,

of learning from experience is a thing of the foreseeable future.

The American scientists Newell, Shaw and Simmons set themselves the task of investigating how the brain solves problems. They developed a programme for an electronic problem solving machine by means of which the machine formulates the best way to carry out its tasks. Such a machine can make correct decisions in the absence of complete information or cut-and-dried algorithms. Thus, it could be used to determine the best applications of old equipment in a plant that is going over to new output. Two other Americans, Hellenter and Rochester, have developed a machine which specializes in proving geometrical theorems.

The development of learning machines has a fascinating corollary: the investigation of living self-regulating systems is now being utilized to produce better cybernetic machines.

Of Cats and Martians

I thought that nothing could surprise me after my acquaintance with learning machines. I was wrong, though, and when I saw a poster announcing a lecture on The Creative Abilities of Electronic Machines I could hardly believe my eyes. The implications of the lecture were made the more fantastic by the array of casual notices on the same billboard informing people of a Sunday ski outing, a meeting of radio hams, forthcoming seminars and sundry affairs of the Institute of Biophysics.

"...and when the course of instruction was completed," the lecturer was saying as I entered

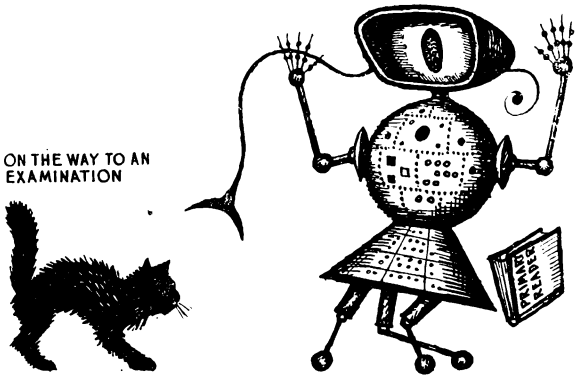
the hall, "the machine signalled its readiness to be examined. To its credit, it was clever and ingenious and did its best to solve the problems presented to it. True, at times it was a bit troublesome. I would say that it behaved like an intelligent person with a queer streak. It developed certain 'prejudices' and we had to introduce a special subprogramme to rid its 'brain' of inhibitions which retarded its work."

A ripple of animation spread through the hall: people were probably impressed by the fact that even a machine was susceptible to weaknesses of its own.

The machine in question was a conventional M-2 electronic computer. The experiment consisted in compiling a programme which would enable it to find answers to problems the methods of solution of which could not be described by strict rules. Such problems are rather guessed than solved, and it was such guesswork that the computer had to engage in.

To begin with, several groups of numbers arranged in lines and corresponding to specific arithmetical rules were fed into the machine. Its job was to use this information to determine the respective rules applied in drawing up another series of numbers.

The lecturer who spoke on the unusual subject of machine creativity was Mikhail Bongard, a young biophysicist. "Our machine," he said, "was in much the same situation a Martian would be on his first visit to Earth. He knows nothing of terrestrial things and we earthmen must explain them to him. We show him photographs of various animals and he sees that one has four legs and a long tail, one has horns, one has a striped skin, and so on. In time you can show him an



elephant's trunk and he will name the animal it belongs to."

The machine acts along similar lines. It must determine the law according to which a group of numbers is arranged from certain characteristics which have not been built into it in advance. It must find them itself. For this it goes through all the numbers in a line to determine their type: integrals or fractions, positive or negative. After thoroughly examining a line the machine can form an idea of it. Depending on whether a given set of numbers corresponds to the first, second, or other specification the machine registers a "zero" or a "one" in its memory store. Each group of lines is denoted in the memory store by a code symbol consisting of thirty "zero" and "one" digits. In this way it determines the underlying characteristic features, and it can quickly establish the law according to which other rows of numbers are assembled.

A Martian does not know which of an animal's features are specifically characteristic of a cat,

a camel or some other creature. Seeing a photograph of a cat taken with a bush in the background he might draw the conclusion: "A cat is an animal with a branch growing out of its ear." And on seeing a cat without a bush he would be quite justified in surmising that it was a different animal.

That is why the machine, like the Martian, must be guided by several features. Irrelevant features, like the bush in the cat picture, must be waived. If, say, all the rows of numbers display a common feature the machine does not memorize it as it is not distinctive. It memorizes only useful characteristics.

Now, equipped with the necessary body of knowledge, the machine is ready for creative work. After being taught arithmetic it can be subjected to an examination. To continue the analogy with a visitor from Mars, the Martian is shown an unfamiliar animal and asked to describe it. He begins with comparing it with known animals, and reasons something like this: "it has four feet like a cat, elephant, camel or wolf; horns like a deer or goat; hooves like a horse. Conclusion: this is a horned and hoofed quadruped."

In the same way the machine takes a new number group, compares it line by line with the criteria selected before and according records "zero" or "one". Having listed the thirty necessary digits it compares the obtained code with the standards stored away in its memory and determines the one it resembles most. Finally it types out: "The given group is most like the sum of squares, known to me."

The machine memorizes not just the numbers shown to it but the characteristic features of the

arithmetical law governing them. Thus it can be said that the machine forms abstract notions. Our Martian, too, did not attempt to name the new animal shown to him, merely designating the type to which it belonged.

Today machines are capable of "discovering" simple arithmetical laws comprising three operations. This is not so little, for the law of universal gravitation, for example, is a two-step problem, and Kepler's third law is a three-step one.

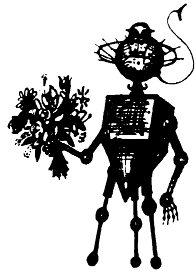
"Provide such a machine with the numbers characterizing planetary motion around the sun," says Mikhail Bongard, "and in a few minutes it will produce Kepler's third law." The author of this unusual remark is confident that in time better programmes will enable learning machines to carry out experimental work. Having exhausted its body of knowledge and come up against something more complicated than anything it knows such a machine will question the experimenter. It may ask, for instance, "Is force really proportional to mass and the square of velocity, as I find it to be from the current data?"

Having been assured that this is precisely the case, the machine will be able to proceed with its investigations. More, it will have memorized the newly acquired information and learned its lesson. The result is the same as if new data had been added to the initial programme. Coming as it does not from the experimenter but from the machine itself, it can be called a programming machine. It is this quality of self-programming that makes learning machines even more like the living brain.

This Martian (or machine, if you prefer) acts not so much like a scientific investigator as like

a person who wants to gain an idea of the whole from a few essential features, like recognizing a familiar face in a silhouette: it mainly imitates the functions of the brain's visual centre.

And this introduces a new aspect, for we find that before asking whether machines will ever be able to "think" we must see whether they will be able to "perceive".



V. PERCEPTION IN MACHINES

Television in the Brain

One of the greatest misconceptions concerning the nature of our faculties of perception is that our eyes see, our ears hear or our nose smells. The fact is that our sense organs are merely receptors specifically designed to pick up stimuli generated by the environment. The eyes detect electromagnetic waves of a certain length constituting the optical region of the spectrum, the ears detect air vibrations of specific frequency and volume, but they do not "see" or "hear". Their task is to translate incoming signals into the language of nerve impulses and transmit them further on.

The perception of light, sounds and other external stimuli occurs in the respective areas of the cerebral cortex: the visual, auditory, taste, olfactory and other areas. The body's sense organs are the brain's receptors which keep it informed of events in the surrounding world, our "feelers directed to the external world", as Sechenov spoke of them a century ago.

The best studied of our body's receptors are those that detect light. For a long time it was assumed that the rods and cones of the retina, which are the primary receptor cells of the eye, operate something like photocells, in which light generates electricity. Later the idea was expressed that they are more like light-sensitive semiconductors. Be that as it may, but essentially their duty is to transform incident light messages into nerve impulses.

The optic nerve, which consists of several bundles of nerve fibres, runs from the light-sensitive retina of each eye to the visual centre situated around the so-called postlateral gyrus at the back of the brain. It is designated as area 17 and is the place where the visual image projected on the retina is interpreted. If this area is damaged blindness results even though the optic nerves are intact. On the way to the cortex the optic tract passes through the subcortical area, which also has a visual centre comprising the optic thalamus, quadrigeminal bodies and lateral geniculate bodies. The pulvinar of the optic thalamus and the quadrigeminal bodies are responsible for transmitting stimuli to the cortical areas controlling the eye muscles. This is a self-regulating mechanism which turns the eyeballs towards the object of interest. It also sets both eyes at the best angle of vision, adjusts the eye lens and dilates or contracts the pupils. The geniculate body is an intermediate station between retina and cortex the exact functions of which are not yet clear.

Our visual system thus appears to be a complex structure designed for the reception and transmission of images, or rather information about images. In this it resembles a television system,

like the one that brings the image to the T. V. set in your room.

"Television in the brain?" the sceptic may say. "Impossible".

I must say that I, too, was sceptical at first, so surprising did the notion seem to me. Nevertheless, the comparison is justified. When physiologists took a cybernetic approach to the system of image transmission in living visual systems they discovered many interesting things.

First of all, they found that the eye does not transmit the images of objects to the brain in a continuous stream. Like cinema projection and television, our eye breaks an image into frames which are transmitted to the brain sufficiently quickly to form a continuous picture.

Besides partitioning the image in time, the eye also breaks it up according to brightness. A mosaic of bright and dark spots forms on the retina, which enables the eye to report on the degree of illumination of observed objects.

In television image details also differ in light intensity, and the transmitted information refers to the illumination of each element of the picture. Imagine that our visual apparatus were completely analogous to television in this respect, that is, that each rod and cone independently transmitted its sense impressions. This would mean that in the time necessary for transmitting one frame to the brain—one-tenth of a second—one million reports about the brightness variation over the image would pass through the optic nerve, which consists of about a million fibres. Within a few minutes the whole cerebral capacity, all 14,000 million neurons would be filled with visual information. It is hardly likely that the "cerebral television" operates in this way.

It has been shown that the eye does not just transmit a visual image from one place to another like television. It screens the visual images for the essential information worth forwarding to the brain.

The optic nerve fibres are not associated with individual rods or cones. This would be impossible if only because there are just a million or so nerve fibres to some 130 million light-sensitive elements in the eye. The rods and cones form groups which are connected with the optic nerve through two intermediary sets of cells. A hundred rods or so connect with a set of 17 retinal cells called bipolar cells. These in turn connect with a retinal ganglion cell. The latter sends the optic messages to the brain. The cones are more "independent" and each one generally connects with three bipolar cells and two ganglion cells.

The intermediary cells between the receptors and the nerve fibre appear to act as accumulators. The rods are weak receptors and the information gathered by a hundred of them is hardly sufficient to form a single "bit" of information for the brain. The cones, on the other hand, are so sensitive that even a weak stimulus evokes a powerful signal and requires several nerve fibres to carry it. The "accumulators "thus play a dual role. They sift messages from several receptors for useful information. At the same time they suppress irrelevant signals entering the communication channel. Their duty is "noise suppression and filtering", as an engineer would say.

The operational cycle of our visual system—one-tenth of a second—can be interpreted as the minimum time necessary for a ganglion cell to assemble the messages from the rods and cones. We see

that our visual system is much more efficient than television, its communication carrying channels are not so heavily loaded and they carry more information in less time. Furthermore, the visual system does not transmit the image continuously as a whole but indicates only the changes taking place in a frame. The nerve cells which transform light signals into nerve impulses are also capable of anticipating changes in the visual image.

Engineers are today discussing the possibility of building television systems in which only "amendments" to the original image would be transmitted. More, instead of waiting for the changes to actually occur they would be "computed" in advance. Nature, however, has long since been employing this method of anticipation. This is achieved by breaking a visual image down into perceptual elements which carry the basic message of the image. These are, in the first place, boundaries between dark and light areas. The eye responds not to a constant light flux but to changes in brightness. If a perceptual element were motionless there would be no variation of light intensity and, accordingly, the receptors would not respond with nerve impulses. But even when one stares intently at one point the eye moves slightly, the elemental boundaries oscillate continuously on the retina and the respective rods and cones receive alternating stimuli from dark and bright portions of the image. It is from these receptors that nerve impulses are sent up to the brain. In this way the eye singles out the contours and specific details of a visual image, that is, the elements of the image in which changes are most likely to occur.

Insofar as the fundamental information about an image is to be found in its contours, it can be assumed that the eye transmits only the general contours of an object to the brain. In fact, the information concerning the visual image may be even more limited.

There are indications that the visual system employs some more complex method of prediction than simply anticipating changes in the brightness of some spot on an image. It has been suggested that vague contours are "subtracted" from clear contours and only information about the difference is passed on to the brain.

To every nerve cell and fibre there corresponds a receptive field in the eye, and the brain can always tell where the messages reaching it have come from. The changes in a visual image are reported by means of a code which is probably based on the number of impulses in a nerve discharge, like the number of shots in a burst of machine-gun fire. A burst may be long or short, with more or less impulses following at greater or smaller intervals. This code has not been deciphered, but most workers agree that the eye transmits its messages to the brain by varying the frequency of nerve impulses, the intervals between them and the duration of each series of impulses.

Each nerve fibre emerging from the retinal cells branches into five or six fibres connecting with the cells of the geniculate body. In its passage through the geniculate body the visual message undergoes some substantial changes. The code gets more refined and the information is compressed, as it were, into a smaller space. Secondary messages are blocked and only essential information is transmitted further on. Much fewer nerve fibres lead out of the geniculate body. They

end in area 17 of the visual centre, where they branch finely, each fibre connecting with some 5,000 neurons. And remember that every neuron can receive signals from several thousand neighbouring cells.

The number of nerve cells receiving the image is not less than the number picking it up, which means that the image can be reproduced here in every detail.

And this brings us to the most interesting and least known element of our "cerebral television", its "picture screen".

Behind the Screen

You are walking down a street thinking of nothing in particular and looking absently about you. Suddenly a familiar figure turns the corner from a side-street and crosses the road away from you.

"Tom (or Dick or Mary)!" You shout, quite sure that it is your friend even though you have caught no more than a fleeting glance of him. Yet you have instantly spotted something familiar, the way he walks or stoops. Even before your mind has registered the visual image your brain obligingly informs you, "There goes a friend of yours."

How do we recognize a familiar face in a crowd of strangers? How does its image imprint itself in the mind? How do masculine features differ from feminine?

It is no use asking physiologists these questions. They can only tell you how the visual system works, how it "receives" and "transmits" visual images, or rather messages relating to various

images. But how does the brain decipher these messages?

Before the complex transformations that visual information undergoes en route from the eyes to the brain became known, the visual centre was regarded as a kind of filing cabinet in which all the elements of the visual image transmitted from the retinal receptors were duly pigeonholed in the respective cortical neurons. We now know that this is a gross oversimplification, yet this has not brought us much closer to an understanding of the way in which the brain perceives the images transmitted to it. This is one of the mysteries which investigators are trying to unravel.

The natural thing was to try and decipher cerebral processes with the help of electroencephalograms. The brain's electrical activity increases when a person is engaged in mental work and subsides when he sleeps. His "brain waves" differ according to whether he is solving a problem or watching a film. Furthermore, rhythms vary not only in intensity but in place of origin as well. I once saw this on the screen of a special instrument. Fifty electrodes attached to the scalp produced fifty bright spots on the screen. As long as the subject sat quietly without thinking of anything the spots glimmered more or less evenly. Then he was given a sheet of paper and a pencil and asked to solve an arithmetical problem. At once the screen showed a fanciful, ever-changing mosaic of light and dark spots.

The bright glowing spot corresponding to the forehead, seemed to represent the main "factory of thought". It consumed most of the brain's energy and neighbouring "affiliated plants" lay in temporary darkness as if contributing their

power to the main plant. The picture of the brain's electrical rhythms is individual and ever-changing and extremely difficult to study. Nevertheless, some distinct patterns of brain rhythms have been observed.

The most prominent rhythm has a frequency of about ten cycles per second and it is most pronounced at the back of the head, in the visual association areas of the brain. These fast rhythms disappear when a person is asleep or looks absently about. They are most prominent when he looks fixedly or studies an object. It was rightly concluded that these rhythms are in some way associated with vision, with the brain's perception of visual images. One hypothesis was suggested by the English physiologist W. Grey Walter, builder of the famous electronic "tortoises" known also by the semi-jocular name of *Machina speculatrix*. We know that the images of objects on the retina are transmitted to the visual centre. They are not deposited there, however, and the visual information is disseminated in some way to millions of other brain cells.

This apparently cannot take place in the conventional way of transmission along nerve fibres. For, Walter writes, "the provision of direct neural communication for the million visual units of the cortex with the rest of the ten thousand million units of the brain would strain the housing capacity of the cranium." The number of nerve fibres would have to be so great that "a house, let alone a human head, would not contain them".

Walter suggests that the visual messages are scanned and transmitted to other parts of the brain in much the same way as an electron beam scans the screen of a cathod-ray tube. A special

centre at the base of the brain emits a continuous beam of scanner waves. These run back and forth across the living "screen" within the visual centre and "pick up" the image. Thanks to this mechanism we not only see things but are able to compare visual images and classify objects according to shape; for example, all spherical objects irrespective of size and colour are classified as "round".

Suppose the images of two different objects are projected on our visual "screen". It has been estimated that it takes our "scanning unit" about one-tenth of a second to compare them. This, it will be observed, coincides nicely with the frequency of the electrical brain rhythms mentioned before. It would thus seem that these rhythms are a manifestation of a periodic process in which an image is scanned on the visual screen. This hypothesis is all the more plausible as the brain rhythms in the visual centre correlate with the time an image is retained on the retina.

In order to investigate this theory in greater detail an attempt was made to break down the electrical rhythms of the visual centre into their component parts. Like a beam of light which breaks down into the seven basic colours of the rainbow in passing through a prism, so the electrical rhythms were broken down into smaller oscillations with the help of a special apparatus. A careful analysis of the brain wave spectrum showed the rhythms to be much more complex than had originally been presumed. For example, the oscillation pattern in the brain of a person taxed with the problem of defining an object by touch displayed great variety and changeability. It would appear that one oscillation component is associated with the naming of the

object, one with its verbal description, one with its visualization, one with imagining its colour, etc. Still, the spectrum was extremely vague, being obscured by irrelevant signals from the same areas engaged in defining the object.

As W. Grey Walter writes, in trying to observe the responses to a specific stimulus against such background noise the researcher finds himself in the position of a man who has an appointment at a crowded street corner with a woman he has never met. They agree that she will be wearing a red carnation, but when the man arrives he finds that other people in the crowd are also wearing red carnations.

Walter and his associates built an apparatus which, they hoped, would enable them to get rid of incidental signals and single out the woman from amidst the crowd of strangers jostling around her. The toposcope, as the apparatus was called, consisted of a display console with 22 small cathode-ray tubes connected with electrodes tapped to specific areas of the brain. In the absence of signals the tubes were dark. When an area functioned the corresponding tubes flashed on. This arrangement enabled the investigators to observe the electrical activity of the brain and the interplay of signals within it. The apparatus also had channels for sending stimuli to the brain, thus making it possible to observe the effects of superimposition of sensations. The toposcope offered a great variety of patterns for observation and many new details in the functioning of the visual centre came to light. When messages of a visual image reached the brain adjacent sections appeared to respond to them in a specific pattern, as if a scanner of some kind were switching them on one by one.

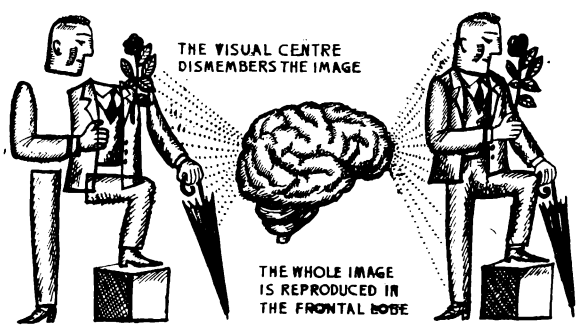
One of the inferences of these and other researches is that the image is "dissected" in the brain and then reassembled into a complete picture in areas lying at some distance from the visual centre. The brain is able to study the "dissected" image in greater detail. Where a detailed analysis is not essential generalized images of objects are formed in other parts of the brain.

With most people electrical activity associated with sight is found not only in the visual area but in the temporal and frontal lobes as well. In the frontal lobes the image is apparently simplified and generalized, superfluous information and nonconstant features being omitted. In the temporal lobes the image persists for some time after the stimulus has ended. If it carries new information or is of interest or importance to the observer it is tucked away into the memory store. An already familiar image is not examined in such detail. However, scientists are not sure that the brain's system of visual perception operates in just this way.

Many researchers are inclined to believe that the most common electrical rhythm of the cortex—10 cycles per second—is of a general nature and is not restricted to visual sensations. It is probably no accident that the lower threshold of audible frequencies lies in the same range, and that rhythms of the same frequency are found in nerve impulses controlling the limbs in motionless positions. That a common rhythm is characteristic of regions of the brain responsible for the perception of external stimuli and for motor control suggests that it may act as a kind of pacesetter for the brain's various mechanisms, which undoubtedly require some sort of synchronization. There is no need for a special device to achieve

this autocorrelation, as Norbert Wiener called it. In Wiener's view the different sections of the brain are "kept in step" in much the same way as electricity generators are synchronized on a common grid.

So far we have been speaking of the highest brain level, the cortex. Of late, however, it has been suggested that parts of the visual image begin to appear in intermediate nerve centres. In any case, it is there that the messages from both eyes are superimposed and compared. As a result the brain gains an idea of an object's size and distance. The basic contrasts of the image are probably also determined at the intermediate visual stations. The task of the cortex is to assemble finally the jigsaw puzzle that is the visual image. This, of course, is the most difficult job. For example, the visual image of a human being must be reproduced from a contour; this means that the brain must connect the characteristic features of the real person with his generalized image. Many attempts have lately been made to explain how the brain does this. Experiments were carried out with lower animals, such as the octopus. An octopus was taught to attack one of two simple figures



displayed simultaneously. In one case the pair would be fairly similar, in another they were less alike. In another experiment the octopus learned to discriminate between a vertical and an inclined line, but it could not perceive the difference between a horizontal and an inclined line. In this way it was possible to determine the features which appear to be most significant for discriminating visual images.

When the scattered facts were summed up several hypotheses emerged. According to one, the neurons of the visual centre, which receive messages from the eyes, are organized in the form of a matrix of rows and columns. In each row there is a cell which sums the stimulus. The vertical lines of an object correspond to excitation of the "summing" cells in the columns, and horizontal lines to excitation of the row of "summing" cells. According to the horizontal and vertical distribution of stimuli in the matrices the brain forms an idea of the shape of an object: the relative distribution of stimuli is different for a square than for a triangle, etc.

The specific dimensions of the object do not matter insofar as in each case it is not the absolute magnitude of the stimuli in the rows and columns that is evaluated but only their ratios. The brain knows a square from a triangle from the characteristic ratio, irrespective of size. Other hypotheses follow similar lines, differing mainly in the structure suggested for the "matrix". Common to them all is that they lay stress on the importance of horizontal and vertical orientation in the perception of the shape or contours of objects. Some points of these hypotheses find confirmation in the structure of the visual area where the nerve processes are clearly arranged

in two main directions, horizontal and vertical.

The theories offer an explanation only of the perception of simple images. They assume that our brain contains something like symbols which denote a square, a circle and other geometrical figures. If this is so the symbols of the simple geometrical figures would appear to be implanted in the nervous system by nature. It would thus appear that we have special "matrices" for perceiving lines within our field of vision. Instead of responding to "on" and "off" light signals, like other nerve cells, they fire only when the corresponding rods and cones are covered by straight boundaries. Cells have also been discovered in the brain which do not respond to the straight side of a square and fire only when a corner of the square enters the receptive field. Finally, some neurons are responsive to movement in a specific direction. They fire only when an object is travelling, say, from left to right across the receptive field.

It is evident, however, that the brain cannot have a full stock of visual symbols imprinted in it from birth. What, for instance, must be impressed upon a cell for it to keep the symbol of a table or a lamp or a hypotenuse, which could not be inherited, for months and years? It is more correct to assume that a set of images constituting a kind of visual dictionary is not intrinsic but is acquired with life experience. The brain can then use simple, elementary images to build up new and complex ones. It does not passively store away the elements of the whole stock-in-trade of the external world. The brain itself creates images of objects and phenomena on the basis of information it receives. These images are not

replicas of the optical images that our eyes see. The brain notes the main features of images and supplements them with mental images. Thus it does not restrict itself to the simple reception of initial information but supplements incoming messages with its own information.

The brain does not like to "compute" an image or to scan randomly for prototypes through a vast store of possibilities. More likely it carries out a selective appraisal of characteristic features, probably by the method of step search, which offers solutions to purely mathematical problems without going to the trouble of mathematical computations.

Seeing Machines

Can a rat tell the difference between a Raphael Madonna and a Picasso Girl in Blue? Could a Martian recognize a live cat after having seen a photograph of one? Could an electronic machine, that crude analogue of the brain, be made to distinguish a cat from a dog or the letter "A" from the letter "B"?

These questions were discussed at length at a special session of the Soviet Academy of Sciences devoted to biological cybernetics, where much attention was given to "seeing" machines.

By now you probably realize the complexity of the task facing scientists who have undertaken to provide machines with vision. The problem is solved neither by introducing an automatic camera to record the surrounding scenery nor by using photocells which would transform incident light into electric current, although the latter, to be sure, does suggest the generation of nerve im-

pulses in the optical tract. The scientists' task is to create an analogue of the visual centre of the cortex. Yet they are not sure of how the brain sees, and it would seem that until they find this out there is no use trying to build machines capable of distinguishing one object from another.

Nevertheless, this difficulty was overcome. If we do not know how to draw up a precise programme of work, let the machine do this itself. Let it learn from its errors and gain from experience. We can then see how the machine coped with its task, and this may offer a hint as to how the brain recognizes patterns. This is one of the reasons why scientists are so keen on developing learning machines capable of pattern recognition.

Workers of Moscow's Institute of Automation and Telemechanics adopted the following procedure. Numbers were written in different ways—each number in two hundred different variants. Forty variants were shown in succession to the seeing machine. At first each demonstration was accompanied by an "explanation", e. g., "this number is '1', this one is '3'." Then the numbers were again presented to the machine, which had to name them. If it made a mistake it was "corrected" and the learning process continued. When it finally learned to recognize forty variants of each number the remaining 160 variants were presented to it. In the initial experiment the first five numbers (excluding "4", which can look rather like "1") were used and the machine had to scan a total of eight hundred digits. It made only four mistakes. In other words the visual images or patterns of 0, 1, 2, 3 and 5 were firmly imprinted in the machine's memory.

How did this happen? The builders of the machine were engineers and mathematicians, and they

approached the problem of pattern recognition accordingly. They did not try to establish how a person distinguishes a "1" from a "5" and teach the machine to do it the same way. They simply devised a mechanical method of recognition.

The machine is shown the first variant of a "1" and a point—the conceptual image—is impressed in the appropriate region of its memory. Then it is shown a second, a third, a twentieth variant of "1" and corresponding points appear in the memory.

The memory store is divided into areas containing the images of all forty variants of each number. The different families of images are kept from mixing by clearly defined boundaries. Teaching a machine to recognize images essentially boils down to the drawing of boundaries between the various families of images in its memory store. Forty points proved to be sufficient for this. In the course of each "reading lesson" the boundaries were shifted in order to bring any points that might be "off limits" into their respective assemblies. The remaining 160 points were projected within the boundaries of their respective assemblies.

Professor Moisei Aizerman, who headed the experiments, points out that he is far from claiming that the human brain recognizes visual images in the same way. "We shall be very happy, though," he remarked at a bionics conference, "if it turns out that one of the brain's recognition mechanisms is of this type."

Workers of the Institute of Biophysics took a different approach to the problem of pattern recognition. They sought to discover how the brain recognizes geometrical figures, landscapes or pictures of animals, and they began by showing

pictures to animals. Physiologists studying cerebral activity were invited to take part in the investigations. Among the first to respond to their appeal was Professor Samuel Briness.

A series of experiments with monkeys were conducted in his laboratory. At one end of a big cage where a monkey can climb and leap about freely there are two doors on which different kinds of patterns are attached. The patterns are very much alike, but not quite. The human eye, at least, can distinguish between them with ease. The monkey's ability is tested by rewarding a correct choice with food. The patterns on the two doors are interchanged according to a table of random numbers. This prevents the monkey from developing a reflex to the specific door behind which the food reward is most likely to occur.

A small capuchin monkey pays not the slightest attention to me. He scrambles to the top of the cage and presses his head to the roof to get a better view out of the window.

"He's looking out for dogs," the laboratory assistant explains. "Come down, Shalun, it's time to do some work."

The little monkey looks down at her but is in no hurry to descend. Finally, after more coaxing he jumps down, runs up to the doors with the drawings pinned to them and pokes one at random. There is nothing behind the door, but this does not seem to worry Shalun, who climbs back to his lookout at the top of the cage.

"The sight of dogs distracts him completely," the laboratory assistant explains. "He refuses to think. You could see that he picked the drawing at random just to get rid of me. Now come down and get to work!" she addresses the monkey in a stern voice. "Do you hear me?"

This has its effect. Shalun climbs down and approaches the doors. He contemplates the patterns for a moment, lifts an arm as if to open the right-hand door, then suddenly changes his mind, opens the left one, grabs the piece of orange behind it and leaps up and down with screams of delight.

"There's a good boy," the laboratory assistant encourages him.

She screens the doors from the monkey, switches over the patterns and invites him to choose one again. This time he makes straight for the darker spot and takes his reward. He "works" confidently through several switchovers until all of a sudden he seems to get confused. He turns back before reaching the doors and huddles in a corner with a doleful whine.

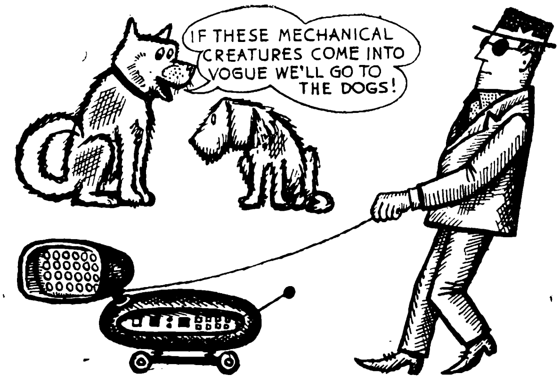
"He's got mixed up and doesn't know which pattern to choose," the laboratory assistant explains, pretending to pay no attention to the monkey. "He'll get back to work when he calms down." She moves something about on the table in a businesslike manner and jots down some notes. Then she turns to Shalun as if nothing had happened. He looks up at her suspiciously and, seeing that his mistake has been overlooked, continues to "work", this time successfully.

"We strive for absolute precision of response. When both patterns are firmly implanted in the monkey's memory we make the task more complicated. Little by little the two patterns get to be more and more alike. In the monkey's brain this develops into something like two assemblies of 'imprints' separated by a 'fence'. The animal's reactions when he is mistaken, when he acts confidently and when he is not so sure offer a key to the way in which it recognizes visual images.

We are thus able to follow the erection of the 'fence' separating close types of image imprints in the brain. Ultimately we shall be able to advise the builders of pattern-recognizing machines."

Such machines already exist and at present they are being taught the alphabet. In the Soviet Union experiments in pattern recognition are being carried out by Mikhail Bongard, the man who "taught" a machine to recognize arithmetical laws according to characteristic features in unfamiliar series of numbers. That work was something of a preliminary training course. The next step was to present the machine with purely visual images of letters. The characters were hand-written and printed, bold and thin, tall and short, roman and italics, upper case and lower case. The machine soon learned to recognize characters according to their specific features and when it was confronted with a letter written in some new way it could generally name it. Although the original "lesson" had lasted only 15 minutes, it sometimes took the machine as much as twenty minutes to name a letter. Sometimes it was confused by similar letters, but then, so are people, and a hand-written "u" may look very like an "n".

In the next stage of the experiment the machine was presented with more dificult images: drawings of cats sitting, standing, running, full face, profile, half-turned. Then funny capering figures of men like those you may have drawn yourself on the corners of a copy-book: when you run the corners from under your thumb they seem to walk, jump and wave their arms. Soon it could tell a cat from the funny little men. Only once it took a cat for a human



figure—and that was when the cat was drawn standing on its hind legs.

A point to be noted is that the machine does not have to be "tuned" to perceive letters or geometrical figures or some other pattern. It just sees and is taught to discriminate between various patterns by an elaborate training procedure. The "instructor" shows the machine an object several times, "punishing" it when it is mistaken and "rewarding" it for correct answers. In this way the machine gradually learns the characteristic features which distinguish one letter from another, a circle from a square, etc.

A very useful design concept for the seeing machine was the "television-in-the-brain" hypothesis, according to which the television principle of line scanning is a sort of primitive prototype of the visual process. The principle was used, for example, in the Perceptron, an American pattern-recognizing machine. A cathode-ray tube is used to transmit the images of objects (triangles and circles) presented to the memory store. The

machine's photocell "eye" transforms light reflected from the patterns into electric signals. To each image there corresponds an electrical code. When the machine's task is merely to identify different objects the relevant signals accumulate in its memory store. When a new image is to be matched with a template in the memory store (as in identifying letters) the signals are sent into the machine's analysing unit. Such a machine can be taught to read.

One of the first reading machines was the Mark 1. It could identify a letter of the alphabet after 15 presentations, every correct choice being reinforced with an appropriate signal. The "eye" of the Mark 1 consisted of 400 photocells and corresponding "nerve ganglia"; its memory unit comprised 512 elements. The "eyes" of some "seeing" machines are fairly close analogues of the retina, complete with the intermediary bipolar and ganglion cells. As in the eye, some of these "cells" fire when covered by a dark portion of the image. The electronic elements form a matrix in which they are joined in horizontal rows and vertical columns. An "on" response of one tube to shade evokes a similar response to shade in four neighbouring tubes. A light signal induces an inhibitory signal in the "shadow-response" photocells. In this way the shadow of a dark object on several photocells does not split into light and dark spots and is perceived as a whole image.

A programme-operated scanning system reviews the states of the "nerve cells" in rapid succession and the data is processed in a computer unit. Such a pattern-recognizing machine is capable of selecting information according to specified features.

Machines can already identify letters and numbers in different types of print. Soon they will

be able to read books, newspapers and other printed matter. Automatic compositors will be installed in print-shops and they will set type straight from typescripts. Some day they may even learn to read handwriting and be able to handle any kind of written matter.

If a machine can be taught to distinguish an "A" from a "B", no matter how they are written, then in principle it can be taught, like Mikhail Bongard's "Martian", to tell a cat from a dog, a microbe from a virus, a spur gear from a roller bearing, in short, to identify objects of all kinds. Electronic laboratory assistants will be built which will take over many of the monotonous and tiresome jobs at clinics and research institutes.

You may have had your blood tested at one time or another, but you may not know how much work goes into each figure in the test report. The red and white blood cells are counted by sight in the eyepiece of a microscope. The eye tires very quickly and no amount of conscientiousness can safeguard the laboratory assistant from mistakes. A whole army of workers is daily engaged in such monotonous counting. Yet the red and white blood cells are quite unalike and an electronic machine could easily be made to identify them faster and with fewer errors than a human laboratory assistant. Similarly, a machine could count the number of bacteria in the field of vision to determine the quality of a bactericidal preparation. At the computer centre of the Joint Nuclear Research Institute near Moscow electronic machines analyze hundreds of thousands of photographs of nuclear particle tracks produced in giant particle accelerators, enabling scientists to pinpoint the specific particles they are looking for. Optical pattern-recognition systems will be

equally helpful in industry. They can be used, for example, to identify machine parts supplied by a conveyer and assemble them together. The time may soon come when electronic assemblers will appear in factory shops to perform operations which have hitherto been regarded as incapable of automation.

But to return to reading machines, in 1961, Dr. Karl Steinbuch, director of a West-German data-processing institute, attended an international congress on cybernetics where he demonstrated a learning machine with an electronic eye which could read vowels. Each letter was represented by a pattern of 90 black and white squares. The input wires of the machine formed a matrix, the descriptions of the characters being fed in through the vertical wires and their meanings through the horizontal wires. The conceptual associations between the graphic symbol and its meaning were formed at the intersections of the array, which Steinbuch called a "learning matrix". Three matrices were superimposed so that the output wires of the first served as the "description" wires of the second, which was connected in the same way with the third. In this three-storey arrangement the first matrix was designed to identify letters, the second, words and the third, sentences.

How can a machine be taught to determine whether a sentence makes sense or not? In the Kiev Computer Centre workers chose fifty nouns, sixteen verbs and the most common prepositions, from which they made up random sentences according to one pattern: noun, verb, preposition, noun. They presented the sentences to the machine, each sentence being followed by the statement "sense" or "nonsense". Thus, "Water flows

on the ground" was put down as "sense" while "The house walks down the street" was declared "nonsense".

After reading a score or so sentences the machine began to classify the words. It identified human beings and the verbs that could be applied to them: think, walk, cook, etc. Other objects (we would call them inanimate) were classified as those which could flow, be poured or cooked, etc. In the next stage the machine was asked to determine whether the sentences presented to it made sense or not. The very first tests were fairly successful, although errors were inevitable. Thus, the machine declared "nonsense" the sentence "The engineer cooks food" (probably it thought that cooking hardly befitted an engineer?). It turned out, however, that the machine had failed to classify the word "engineer" in the "human" group of nouns. Additional explanations were duly fed into it. The error, though, suggested an interesting line of investigation, and the researchers decided to see how the machine would distinguish between human beings and animals.

These experiments are still in their infancy stage, but they hold promise of exciting prospects. As Karl Steinbuch remarked, "The next decade will most surely see the creation of machines capable of reading and understanding speech."

Hearing and Talking Machines

One of the first conversations between an electronic machine and a human being took place several years ago at the University of Toronto. The man was the Canadian scientist Edward Berkeley. Three hundred common English words

had been stored in the machine's memory, and it was taught how to use them. The conversation was banal, and did not go beyond a discussion of the weather. The important thing, though, was that it made sense, and in one case the machine even displayed a sense of humour as it exposed a contradiction in Berkeley's remarks.

The possibility of building electronic interlocutors is being widely debated and one might even gain the impression that they may appear any day. Before a machine can engage in meaningful conversation, however, it has to be taught the art of speech perception. A conventional microphone is not enough for this. An electronic ear is necessary which would be capable not only of detecting sounds but of identifying them and the words they form. In short, it must be capable of understanding speech.

The very special question which once interested only linguists and language teachers—the ways in which the sounds of intelligible speech are produced—has become the concern of electronic engineers and scientists. They study the vocalization of words by joining sounds in unusual combinations, "cutting" them into pieces, isolating sound components and performing all kinds of ingenious experiments. In the Soviet Union these investigations are being carried out by laboratories of experimental phonetics in Moscow, Leningrad and Tbilisi.

In such a laboratory one finds three-dimensional representations of vowels and consonants, syllables and whole words which look like papier-mache models of mountain ranges or icebergs. Voices of different kinds are represented in coloured drawings in which shades and hues show how pitch and tone change in the utterance of words

and syllables. There are devices for recording, "dissecting" and "recombining" sounds. A sound spectrograph shows how sounds are made up of several frequencies and intensities. A sound separator isolates a portion of a recorded sound no more than three- or four-hundredths of a second in duration. Here the researchers will play back to you the warbling of birds, opera arias, pop songs, the carefully articulated speech of a radio announcer and the gibberish of a recording played backwards.

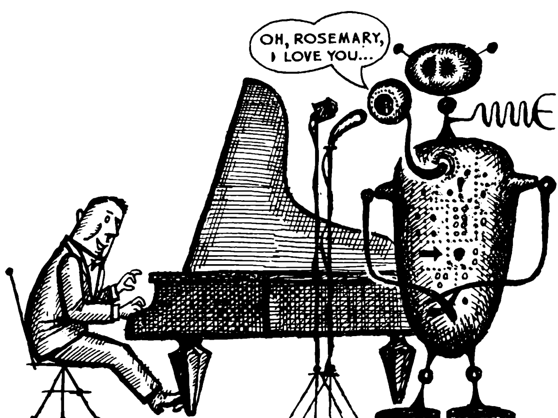
The researchers have discovered many interesting features of speech sounds. Thus, the spectra of vowels contain many redundancies. A vowel can be "clipped" substantially and still be recognized for what it is. Although vowels are made up of several formants, or frequencies, they found that two formants are sufficient to make a vowel recognizable. Furthermore, within a meaningful word a vowel can be mutilated practically beyond recognition, yet the brain will recognize it. If a word of several syllables is pronounced with no stress whatsoever the brain itself tends to rectify the omission and place the stresses as required. This was demonstrated in an experiment carried out by Professor V. Artyomov, head of the Moscow Laboratory of Experimental Phonetics. Artyomov, who is studying the psychological aspects of speech perception, played off a "flatly" pronounced Russian word to a group of students, several of whom had no knowledge of Russian. The subjects knowing Russian reported that they heard the word properly stressed, the non-Russian speaking subjects heard no stress in the word.

This simple experiment offers an idea of but one of the difficulties facing the designers of machines capable of understanding speech and speaking

meaningfully. Human perception of a spoken idea frequently depends on the extent of a person's knowledge of the subject and the language as well as on the context in which the words are spoken and environmental circumstances.

In order to produce a real talking machine—not a tape recorder, telephone or loudspeaker, but a device capable of articulating speech sounds by itself—it must be supplied with a prototype of the human vocal apparatus as well as with an electronic ear.

Nature has provided us with an extremely complex and sensitive hearing apparatus with which no microphone can compete. It is located in the middle ear and begins with the eardrum which transmits sound vibrations to a helical structure called the cochlea. The cochlea contains a membrane on which rest the sensitive cells that excite auditory nerve fibres. The sense organs in the basilar membrane, as it is called, can be likened to the strings of a piano which are tuned to tones



of different frequency. The auditory pathway ends in the temporal lobes on both sides of the brain where the auditory centres are located. In the final analysis it is the latters' operations that must be duplicated for a machine to be a worthwhile interlocutor.

Existing talking machines are largely in the baby-talk stage. True, a machine built at the Tbilisi Institute of Automation and Telemechanics can speak the magic phrase: "Our machine has studied, it knows life." It articulates the words very carefully and precisely and it can speak in a male, female or child's voice. Nevertheless, it is not a human voice, it has a "mechanical" quality and lacks the warmth of human timbre and inflections. It is completely impassive, flat and neutral. In 1961 the machine even spoke over the radio to send greetings to Nona Gaprindashvili, the Georgian world women's chess champion. "Be attentive, dear Nona," the machine said in its impassive voice.

Well, as far as the engineers are concerned, toneless speech is quite sufficient for a machine designed for industrial process control, which is probably the first job it will be given. Industrial operatives, dispatchers and overseers are usually confronted with such an impressive array of blinking lights, dials and oscilloscope screens on their control consoles that they can hardly keep track of all the incoming data. A talking machine would be able to call the operator's attention when necessary and report the state of affairs. It would be even more convenient for the operator if he could merely speak an order into a microphone instead of manipulating push-buttons.

At the Tbilisi institute there is a little "tortoise" which obeys simple vocal commands:

"straight", "reverse", "left", "right", and "stop". It can be tuned so as to obey only its master's voice. So far it travels about the floor of the laboratory. Its progeny will appear as rolling mills, tractors and other mechanisms operated by vocal control.

A Signal of Signals

"Patient M., 52 years, literate, right-handed, admitted August 23," I read in a case history at the Neurological Institute in Moscow. "Complains of distortion of visual perception. Several days ago, while hanging a picture on the wall, bent his head back, felt sudden pain, lay down and closed his eyes. Later got up and went to the window. The houses on the other side of the street seemed strangely flat. Recognizes familiar objects and acquaintances with difficulty..." I turn over several pages of clinical analyses and tests to the neurologist's conclusion: "State of patient unchanged. Sees people but does not recognize them. Guesses who a person is by indirect features: a familiar scarf or voice. Views own reflection in a mirror as a stranger. Describes individual features of a drawing but does not understand it as a whole....

"Diagnosis: visual agnosia." In the margin is a note: "Cortical areas 19 and 39 are probably affected."

A strange ailment, is it not? Something is wrong with the patient's vision, yet he has been placed in a neurological clinic where diseases of the central nervous system are treated. One could expect the patient's visual centre to be affected, but areas 17 and 18 are intact while the affected

areas 19 and 39 apparently have nothing to do with visual perception. (Area 19, to be sure, borders on the visual area, so it could be associated with vision in some way.) The fact is, of course, that the patient sees objects. Hence the cortical areas responsible for simple visual perception are in order. Affected are certain higher functions of the brain thanks to which we recognize familiar objects and people on sight.

There are many variants of this disease, they told me at the Neurological Institute. A patient may recognize objects visually but does not comprehend sounds and he cannot tell an automobile by the sound of its horn or a clock by its ticking. In this case a border area of the auditory centre is affected—area 39 again. In another case a person sees and hears normally but cannot tell things by touch: affected are a part of the area responsible for tactile perception and, of course, area 39.

This mysterious area can be found on a chart of the brain between the occipital lobe (where the visual centre is located), the temporal lobe (where the auditory centre lies) and the parietal lobe (seat of the tactile centres). It occupies a fairly large region and is responsible for some of the brain's most important functions. In fact, 39 and neighbouring 40 are areas which occur only in the human brain. They developed late in the history of mammallian evolution and are responsible for abilities unique to man: cognition and purposeful work. In fact, they evolved in the process of work.

Work, which transformed ape into man, developed a section of the cerebral cortex specifically for the purpose of analysing changes in the environment created by purposeful activity. Work as a process must be organized and conducted accord-

ing to plan. This is handled by area 40. In the course of his life man acquires a vast number of skills and abilities, which he retains as long as area 40 functions normally. If something goes wrong there a person is unable to go through familiar actions or use familiar objects. He cannot dress himself, button his shirt or pour a glass of water. Even if he can cope with simple actions, he cannot perform complicated ones and, especially, abstract actions, like going through the motions of eating out of an imaginary plate with an imaginary fork and knife. In such a manoeuvre as, for example, lighting a cigarette, he may strike a match on the smooth side of the matchbox or put the match in his mouth and strike the cigarette. Neither can such a patient draw a simple pattern or construct a simple geometrical figure out of matches.

In this case, too, it is not the control of a specific movement that is affected (the motor centre is functioning normally) but the general plan of action, the labour skills developed by learning and experience. What is involved is the highest form of motor activity evolved by man.

At the same time, though, it cannot be stated unequivocally that area 39 is responsible for cognition and experience and area 40, for purposeful work and action. The highest nervous functions are carried out by the brain as a whole. This is especially apparent when speech is examined. Speech evolved in the process of work, as a means of sharing experience and ideas, and verbal communication is the most recently acquired function of the human brain. Obviously it could not fail to bring about changes in the brain's structure.

"When the developing animal world reached the stage of man," writes Ivan Pavlov, "an extremely

important addition was made to the mechanisms of the nervous activity. In the animal, reality is signalized almost exclusively by stimulations and the traces they leave in the cerebral hemispheres, which come directly to the special cells of the visual, auditory or other receptors of the organism. This is what we, too, possess as impressions, sensations and notions of the world around us, both natural and social—with the exception of the spoken or written word. This is the first signal system of reality common to man and animals. But speech constitutes a second signal system of reality which is peculiarly ours, being the signal of the first signals."

With the second signal system is associated the specifically human ability to abstract from the countless stream of specific information pouring in through the first signal system, to summarize its essence. For this some specified quality of an object must be designated by an arbitrary sign which could serve as a symbol of that object in any conditions. This "code sign" is the word, a "signal of signals". The system of word perception is the second signal system, in which the conditional stimulus is the word, spoken, heard or seen. The brain must be able to identify a word in whatever form it appears, establish connections between different words and, in the case of speech, mentally construct a word or even a whole sentence before the lips utter it.

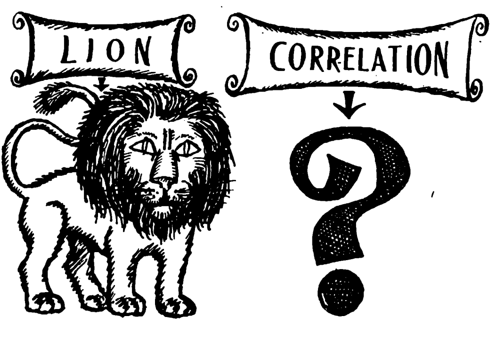
When scientists thought that the brain possessed a "collection" of images of the objects and their parts belonging to the world around us their idea of the second signal system was rather primitive. Words are the names of objects, hence all that is required is to project the elements of the first system on to the second and we have

another collection in which each image in the first corresponds to its name in the second.

But, the physiologists began to ask themselves. what are such words as "again", "without", "however", "or" the signals of? Where are the various grammatical variants of words located, such as "you see", "he sees", "they have seen"? And what about such word signals as "wave function", "correlation" or "differential"? It seems obvious that, although there is a close connection between the first and second signal systems, it is not the simple geometrical projection suggested before.

Having got used to the idea that all functions of the brain are more or less closely associated with specific areas, I wanted to find out where the speech centre is located.

"There is no such centre," they told me at the Neurological Institute. "A number of areas in different parts of the cortex are associated with speech in one way or another. The motor, auditory and visual centres of speech are each associated with one of the three actions: speaking, hearing and reading. In speaking or writing, in reading out loud or to oneself different sections of the speech complex come into play. This is especially



apparent when one of them malfunctions. Various impairments of speech fall under the common heading of aphasia". And this brought me to the neurological clinic of Dr. Esther Bein, a leading Soviet aphasiologist.

When I came to the clinic Dr. Bein was examining new patients. She invited me to attend the procedure. The patient happened to be a woman who had lost the ability to speak. Dr. Bein had to determine the exact nature of the affliction.

"Well," she began, "let us get acquainted. I am your doctor. Now tell me what's the matter."

The woman attempted to say something but failed hopelessly and reached in despair for her handkerchief. So much for the first stage of the examination, Dr. Bein explained, which is to determine if the patient can articulate words and if the motor centre of speech is functioning. The next stage is to test her understanding of grammatical constructions.

"What statement makes sense and what doesn't: 'The sun shines on the earth'; 'The earth shines on the sun'?" Dr. Bein repeated the two sentences very slowly and waited in vain for an answer. "Which of these two sentences is correct: 'The hunter shot the bear' or 'The bear shot the hunter'?" Again the patient could not answer.

"Put the pencil ON the book," Dr. Bein went on, stressing the preposition. The woman shuffled the book and pencil about as if she didn't know what to do with them. "Put the pencil ON the book," Dr. Bein repeated very distinctly several times until the woman finally managed to carry out the request.

"Now put the pencil UNDER the book." Again the woman fumbled clumsily with the pencil and the book before she could carry out the order.

Dr. Bein made a note and went on with the test. "I shall dictate a few words which I want you to write down."

The woman took the pencil awkwardly as if she were just learning to write. The first few letters, though shaky and scrawly, were legible. Then her hand slipped off, the sheet and the pencil fell to the floor. "Disorder of written speech," was Dr. Bein's conclusion. "Nevertheless, if all goes well she'll be all right in a couple of months."

I spent a whole day at the Neurological Institute, visiting wards and observing patients in various stages of disease and recuperation. The great variety of speach disorders gradually revealed the complex but orderly mosaic of excitations and inhibitions in various cortical areas which lies at the basis of sensible speech. Disease disrupts the orderly system, and this shows up the constituents of that remarkable ability of the human mind called speech.

The roles of the two cerebral hemispheres are not the same in speech processes. It is well known that our left hemisphere is generally more developed than the right, and the right hand, which it controls, is stronger and more deft than the left hand. A disorder of the left hemisphere generally results in more or less serious disorders in speech and writing. This, of course, goes for right-handed persons. With left-handed people the reverse is true, which explains the entry "right-handed" in the case history cited at the beginning of this section.

Speech is essentially the articulation of words and the individual syllables which make them up. The main part in this process is played by the third left frontal convolution around which areas

44 and 45 are located. This is the motor centre of speech, which developed with the need to move the lips, tongue and larynx to articulate sounds. A disturbance of this area makes articulate speech generally impossible or restricted to a few ill-pronounced sounds, although the patient hears and understands words quite well. A minor lesion of the area may result in various degrees of speech impairment. Analogous difficulties may appear with writing, that is, in the ability to correlate the motion of the hand and the attendant movements of the head and eyes. When we learn to write, a plan of movement gradually develops in the brain which enables us to draw a letter. Formation of this plan, like all of man's purposeful activities, involves area 40. If it is affected a person also loses his ability to write, though for a different reason since what has disappeared is the plan of work to be followed by the hand.

Articulate speech also proceeds according to a definite plan. Each action in producing a sound is followed by an analysis of its results in the auditory, or word, centre, by a kind of mental playback. This verification of word build-up is carried out by the anterior part of area 22. If it is affected a person may be unable to build a word out of correctly articulated syllables. When connections between the motor and auditory centres are disturbed a person tends to transpose syllables and letters in the manner of the Reverend William A. Spooner, or worse, and extra letters will crop up.

Area 22 is located in the temporal lobe and, together with the neighbouring area 21, it constitutes the auditory speech centre in which oral speech perception takes place. When the centre

is affected a person ceases to understand spoken words, just as in disturbances of the visual (word) centre a person fails to comprehend written or printed words.

Intermediate between the auditory and visual centres are area 37 and the aforementioned area 39. When area 37 is disturbed a person is unable to name familiar objects and will speak of a knife as "the thing for cutting" or a glass as "the thing for drinking from". Such disorders can also be caused by a disharmony in the functioning of different speech centres or by a malfunction in the transmission of nerve stimuli from the first to the second signal system.

Similarly, the perception of written letters and combinations of letters is dependent not only on the faultless functioning of area 39 as the "recognition centre". It may often be a result of disorders in temporary connections between the visual, auditory and motor speech centres. When we read we mentally translate the visual image of words into inner, voiceless speech, and the auditory and motor speech centres must also take part in this process.

Our consciousness does more than simply project images of the external world. We perceive the essence of phenomena, their dependence on such physical entities as space and time. Speech must convey the specific relationships of objects and phenomena in space and time. This is achieved by means of grammar, the use of word inflections and prepositions, articles and other auxiliary words. When area 46 in the frontal lobe is disturbed a person loses the ability to construct sentences according to the rules of grammar and is unable to describe in words the interrelationships of things in space and time.

In listening to somebody or in reading a book we must be able to comprehend sentences grammatically. This is impossible when areas 37, 39 and 40 are disturbed, and a patient may be unable to tell the difference between "father's son" and "son's father" (or between "the sun shines on the earth" and "the earth shines on the sun", as in the case of Dr. Bein's patient). A patient may understand a sequence of events in such a sentence as "I went for a walk after work" according to the word order, that is, that the "walk" preceded the "work". A request to draw a cross over a circle (or to put a pencil under a book) is also carried out according to the word order rather than the inner logic of the sentence, and the patient will first draw the cross and then the circle under it.

All this offers an idea of the complexity of the brain's second signal system. Scientists have still much to learn about the interrelationships and interactions of the various speech centres among themselves, as well as with the visual, auditory, olfactory and other centres of the first signal system.

Transmission Capacity of the Brain

Any higher psychic activity of the brain must be based on the transmission of signals, however complex or second-order they may be; as a result it is possible to study the brain, like the nervous system as a whole, from the point of view of information theory. This is a mathematical discipline which deals with the transmission of information in communication systems. They may be technological systems like the telephone, telegraph and radio, but they may also be the phys-

iological systems which transmit messages in the living organism.

In the organism messages are delivered to the brain, which processes them and sends out the necessary commands. Information reaches the second signal system in a similar way. How long does it take to consciously process information?

Suppose a person is offered to arrange a thoroughly shuffled pack of cards in suits or an experienced typist is asked to type out a random set of letters. In both cases the person must mentally analyse the nature of the signal and choose a suitable response. The time needed to comprehend what is taking place and respond to the external stimulus is that which the brain takes to process the information about the type of signal. By applying information theory psychologists have found that the brain operates as an optimal communication system, that is, it is the most rational one.

The experiments used to reveal this are designed so as to replicate the process of information transfer along technological communication pathways with man as a part of the general transmission circuit. This enables the scientists to investigate the special features of information processing by man and thus to establish how human systems differ from mechanical ones.

One day I was invited to be the subject of such an experiment. This was at the department of psychology of Moscow University whither I had come to find out about modern psychological research. The room was more like a physical laboratory than anything else, what with its formidable array of recording instruments, oscilloscopes, control knobs and signal lights. A door at one end of the room led into a metal-

plated windowless compartment. The laboratory workers, associates of Professor Leontyev, invited me to get in and occupy the only seat in front of a small console with what looked like two telegraph keys on it. Facing the seat was a panel on which there were several electric bulbs. In response to different light flashes I had to press one or the other key or say some word or meaningless combination of sounds.

During the experiment the door is tightly shut to seal a person off from the outside world. It is something like the "silence chambers" in which astronauts pass endurance tests lasting several days. Here, of course, the voluntary confinement is much shorter as the purpose of the test is different: a person must respond to a complex of signals following a pattern drawn up by the psychologists. An hour of such work is a pretty exhausting experience.

The experimenter outside the chamber switches on the various signals in random combinations. The subject must respond to each signal in a certain way. He does not know the order in which the signals will appear and his mind is concentrated on the sole task of giving the correct response to a given signal. A series of such experiments enables the investigator to establish the dependence between the response time and the amount of information carried by a given signal, and consequently, the rate at which the brain perceives it.

The British psychologist W. E. Hick, one of the first to undertake this kind of experiments, came to the conclusion that our brain processes information at the average rate of 5 bits per second. His findings, however, were based on a relatively small number of equally possible

signals. Furthermore, he judged of the results only according to the motor or verbal response, without taking into account the reaction time of the subject. Obviously, when signals appear at random intervals the brain must be constantly on the alert. Besides, signals may differ in significance. For example, the signals to be taken into account by an operative at an automatic production line will include routine reports of temperature and pressure as well as alarm signals in case of breakdown.. Will the brain take as long to deal with the alarm as with the routine signal? In other words, it is not enough to go by the average amount of information carried by a dozen signals. It is necessary to take into account the significance of each signal.

These purely human features of information processing are being studied by psychologists at Moscow University. In one experiment one of two signals was designated as an alarm and a subject was required to react with utmost speed. If his reaction was too slow, the device "broke down" (the experimenter switched off the instruments). The assignment of different significance to the signals immediately reflected on the results. When the subject was alerted to the possibility of a signal of special urgency the brain responded to the alarm much quicker.

Thus, in a human system the significance of a signal is of great importance. It stimulates the brain's ability to perceive information and cope with it more efficiently. Yet information theory generally ignores the significance of a message. What matters is the number of letters needed to transmit it. This is the case in engineering communication systems. Our brain, however, works according to an entirely different principle, and

it dispatches important messages to the hands or feet or vocal chords much faster than routine messages. This is one of the important distinctions of the living brain from the very best automatic data-processing machine.

The brain responds differently to frequent and rare signals. In the course of an experiment a subject consciously or subconsciously memorizes the probability pattern of the signals. It is as though he mentally constructs a model of the signal complex employed by the experimenter and tries to anticipate events. As a result the brain is alerted to rare signals and when they occur the response time is much shorter.

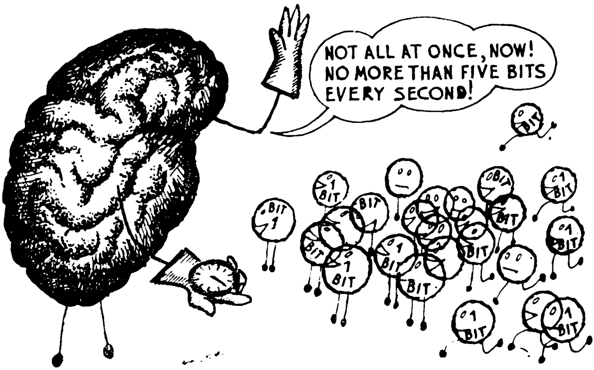
To be sure, this is achieved at a penalty, and the perception and response to the more frequent signals slows down. Nevertheless, such an internal mobilization of the organism is useful. If this did not happen the response to rare signals would be slower than to frequent ones—or at least that is how it should be according to classical information theory.

Possibly the speed of a response is also affected by its complexity. To verify this the Moscow psychologists raised the number of signals to ten and increased the complexity of the responses required from the test on objects. They concluded from their experiments that the speed of information processing varies depending on circumstances, but in any case it is much higher than Hick's average. Confronted with a situation in which a choice must be made, our brain is capable of consciously handling 25 bits of information per second. As to its capacity "in general", it is hard to give a specific number. The organism's various "communication channels" possess different message-handling capacity.

For the sake of comparison, your television set, if you have one, handles a million units of information a second. Our eyes are capable of transmitting about as much information to the brain. Computing machines process a thousand times less information, as does another of our "communication channels" with the outside world, touch. The capacity of radio and telephone systems is another thousand times less, and our auditory organs are about on a par with them. Inside the brain information is processed about half as fast as in a telegraph apparatus, which handles one hundred units of information per second.

According to the German psychologist Helmer Frank, whatever reaches the brain remains in our consciousness for ten seconds. This is demonstrated by the following example: suppose you are engaged in some business of your own and the clock begins to strike. If you have suddenly become aware of it when it has made five strokes you will be able to count them, for they will still be in your mind. On this basis Dr. Frank compares our active memory, which retains images and echoes of signals within our consciousness, with a short-term storage device, as distinct from the memory's archives which store information indefinitely and independently of our consciousness. He even calculated the approximate volume of this short-term storage system.

First he undertook to determine the bottom threshold of the brain's message handling capacity. He made several students write down everything they saw on a screen where rows of letters were regularly flashed on every tenth of a second. One might think that if the projection time were doubled a person would be able to perceive double the information. Actually this was



not the case, and in each additional second 16 units of additional information were perceived. This is the lower threshold of human perception.

Sixteen bits per second retained for ten seconds implies that our short-term memory capacity is 160 bits. Out of this number, only 0.7 bit, or 1/25th of what we perceive, is stored in the brain's archives. As much information escapes from our head every second, making room for new messages.

A part of the information is used up to take stock of our impressions. If a title is flashed on a screen, say, 8 bits are used to carry information about the stimulus itself and another 8 bits are used up to determine the meaning of the word. Many researchers consider that only half of the 16 bits is directly perceived; the other half is expended on extracting pertinent data from our memory store.

Be that as it may, but it is apparent that not much information passes through our mind at a time. Yet it is enough to set the whole complex programme of our thinking system into operation.

It must be said that man's conscious activity is a very peculiar and complex thing. Alexander Kolmogorov cites a paradoxical example in this connection. He has calculated that a slalom racer speeding downhill perceives and processes more information in nine seconds than a mathematician in forty minutes of intense calculations.

Language and Information

Lewis Carroll hardly had cybernetics in mind when he wrote of Alice's adventures. Even less could he have considered its applications in linguistics.

"It is a very inconvenient habit of kittens (Alice had once made the remark) that, whatever you say to them, they *always* purr. 'If they would only purr for "yes", and mew for "no", or any rule of that sort,' she had said, 'so that one could keep up a conversation! But how *can* you talk with a person if they always say the same thing?'"

Information theory specialists would rate the kitten's "language" as low as Alice did. "A message consisting of a repetition of the same sound (or letter or word), "they would say, "carries no information." From the point of view of information theory, language is a code used by people to record and transmit information. Stripped of content and qualitative diversity, all speech communications are similar, comprising as they do a definite sequence of sounds, letters or other arbitrary symbols, like the dots and dashes of the Morse code.

In any meaningful message different letters will quite naturally appear with different frequency. It comes as a surprise to no one that the

number of words under each letter heading in a dictionary varies. This is due to the rules of language. That different letters occur with different frequency is also well known. Typists and printshop workers are especially well aware of the relative frequency of different letters. A typesetter's case is accordingly divided unevenly so as to take account of this linguistic feature.

Today languages are being subjected to mathematical study, giving rise to the new science of mathematical linguistics. Scientists study the relative frequencies of letters and various combinations of two, three and more letters and develop corresponding mathematical formulas. Thus, an analysis of various Russian texts with a total of 88,000 letters revealed that the average occurrance of the letter "o" is nine in one hundred letters; "a" occurs six times, etc. Similarly, the relative frequencies have been determined of various combinations of two, three and more letters, and of syllables. The length of words varies in different languages. Thus, in Russian the average word has 2.2 syllables, and only 3.5 per cent of Russian words consist of five syllables.

Mathematical linguistics deals, as mathematics should, with percentages, formulas and graphs. I was shown graphs characterizing the language of Shakespeare, Aldous Huxley, Ceasar and the Roman historian Sallust. The Shakespeare curve revealed that he, like all writers in English, employed more one-syllable than two-syllable words. The Latin authors, on the other hand, used an approximately equal number of two-, three- and four-syllable words, in compliance with the rules of the language.

Mathematics and cybernetics applied to linguistics enable the amount of information car-

ried by letters, words and texts to be determined. Information, you recall, is measured in bits. Another name for the unit of information is "yes-no unit". This name is probably more to the point, as the unit is equal to the minimum information carried by the answers "yes" or "no". Any of these two answers removes the indeterminancy of a situation, for instance, when you are reading the message being typed out on a moving telegraph tape. The appearance of each subsequent letter removes indeterminancy in the content of the message and substitutes the knowledge provided by the information contained in that letter.

How much information is carried by a letter in a real sentence, subject only to the condition that the sentence be meaningful? For an otherwise grammatically correct sentence may be quite meaningless, such as, "The train jumped from the roof". Formulas can be used to calculate the amount of information only in apparently meaningless combinations of letters, even though they take into account the laws governing combinations of two or three or four adjacent letters. The task is to determine the internal information of every letter in a meaningful context.

Claude Shannon, one of the founders of information theory, suggested the following procedure. First, compute the amount of information per word according to its relative frequency. The average for the English language is 11.82 bits. The average length of an English word is 4.5 letters. Hence, the amount of information per letter is 2.14 bits.

And now what? How to take into account the association of different words among themselves? Here, too, Shannon suggested a subtle roundabout way.

Every person subconsciously or intuitively feels the statistical structure of his native tongue. When a person is offered to guess the continuation of a sentence—letter by letter and even word by word—he will, with little hesitation, usually name the next letter correctly. Such experiments, in Russian, were carried out at Moscow University at the department of probability theory, headed by Alexander Kolmogorov. He found that the internal information carried by one letter in a meaningful Russian sentence is not five bits, as theoretical calculations suggest, but less than one. Each letter of the Russian alphabet carries one fifth of the information it could. In other words, the "language code" suffers from redundancy. This property of the language was not known to linguists. It took cybernetics to discover it.

Broadly speaking, we may say that redundancy is an indication of the percentage of "extra" letters in the language. Suppose you are asked to guess the unknown letters in a sentence when you are given some initial ones. Say, out of a sentence of 129 letters you have guessed 89, or 69 per cent, correctly. This means that the letters are "redundant", insofar as they can be predicted according to the rules of the language.

Of what use are redundant letters? In engineering jargon, they make a communication noise-proof. In a random selection of letters the redundancy is zero, and the omission of a single letter distorts the message, if any, irreparably. In a real meaningful phrase in which all the rules of grammar and syntax are observed redundancy is fivefold. The redundancy of the Russian language was calculated by workers of the Institute of Information Transmission Systems in Mos-

cow who analysed passages from Leo Tolstoy's *War and Peace*.

For the English language the redundancy was calculated by Shannon, and similar data have been obtained for the French, Spanish and German languages. The redundancy of Spanish was found to be very close to that of English, French is slightly less, and German a bit more redundant. The redundancy of all European languages is considerably above 50 per cent.

In poetry, it was found, each letter carries about 50 per cent more information than in prose writing. The reason is that in poetry the laws of syntax are not so strict and word order is freer than in prose. Grammar, too, is more flexible, and furthermore, poets often use words which we do not use in ordinary speech. On the other hand, rhythm and rhyme exclude many arbitrary means of expressing the same idea. A poem may be said to carry information in more concentrated form.

It would be interesting to compare the redundancy of languages in which words are formed and joined in the sentence according to different laws: say Russian, with its six cases and three genders, and English, which has only one case inflection and no gender inflections. Which language "works" better? It is suggested that the redundancy of Russian grows much faster than of English, which means that it is more "noise-proof".

These linguistic investigations are of great use to communication engineers. Information theory is helping them to compile much more economical—less redundant, that is—telegraph codes than are presently used. And there is another field in which scientists would like to develop a language with minimum redundancy.

Machine Language

I must confess that I was more astounded by the news that scientists were working on a language for machines than by numerous reports of the growing abilities of "intelligent" machines. All these cybernetic wonders, as I have already said, are easily explainable. More often than not the case usually is not that the machine has become more "intelligent" but that automation has been extended to another field of what was once regarded as purely human activity. All kinds of seeing, hearing, reading and speaking machines fall into this category without exception. All they can do is copy human activity more or less faithfully. They do not need a special language of their own, as we have seen.

But when it comes to a special machine language, does this not mean that machines are gaining independence? My imagination conjured up visions of machines sarcastically challenging orders or peacefully discussing the prospects of cybernetics with their creators. What, I wondered, would happen if an argument flared up? Joking aside, however, why did the problem of a machine language ever arise?

It all began when the problem of translation from one language to another by computers was tackled. The very first translations (of very scientific and technical texts) were word-for-word substitutions. Since the languages used, French and English, have broadly the same grammatical structure, the first experiment in word-for-word translation was more or less successful. But between, say, German and Russian such a method of translation is impossible. In German the verb is usually at the end of a sentence, in

Russian its position is not so rigid, and there are more serious difficulties due to differences in grammatical structure.

The thing to do, then, is to teach the machine grammar, that is, establish the relationship between the rules governing word combinations in different languages and feed the information into the machine. Then it must be acquainted with syntax, the rules according to which the parts of the sentence are arranged. It was here that the scientists found that the rules of grammar and syntax employed in language teaching are much too complex and involved. They were drawn up by linguists very long ago and largely on the basis of speculative reasoning. Machines cannot operate with such inadequate grammar, and the rules were subjected to mathematical treatment. The result was that secondary rules were either abolished altogether or included under the heading "exceptions". The rules became more compact in that they dealt with the main features of the language and were not concerned with unessentials.

In part these changes were concerned with internal grammatical structure. Machines, for example, could not "understand" the then existing classification of parts of speech. Words had to be classified more simply. When this was done the linguists thought: Why not transfer this principle to conventional "human" grammar? Maybe the very definition of "part of speech" should be revised and its meaning made more precise, as suggested by "machine" grammar? From this it was natural to suggest that languages in general be studied according to a simpler grammar.

While the linguists were debating the question the cybernetic translators came up with new

demands. "You have given us excellent rules for machine translation," they said, "but they are good for only two languages. For machine translation to become a paying proposition we need multilingual machines." They might have added that besides being restricted to two languages the mechanical translators were further restricted to highly specialized scientific vernacular, such as chemistry or electronics.

It was not this kind of machine that the scientists dreamed of. They wanted machines capable of translating back and forth among ten or twenty different languages. But in this case the number of rules would swell enormously. A way out was suggested through the introduction of an intermediary machine language. In this case there would be only two sets of rules for each language, one for translating into the machine's language and one for translating back into the human tongue.

Various intermediate languages were suggested: one of the simpler existing languages, or an artificial language like Esperanto or Interlingua, for example. They were rejected, however. A machine language had to be something like a universal key which would open different kinds of locks and, furthermore, be as unredundant as possible.

Different workers took different approaches to the problem. A team of Leningrad linguists, for example, is devising a completely new language with a vocabulary and grammar of its own. Its structure will be based on the principal characteristics of a number of the most widely used languages. The workers took 26 European and Eastern languages, which they analysed to develop something of an "arithmetical mean" for every grammatical and syntactic rule. They also took

into account the number of people in the world who use the language for daily communication. They concluded that in the "intermediate" language an adjective must always precede the noun it modifies, the subject must always come before the predicate, an adverb before a verb, etc. They found no use for the article. At present an experimental variant of such a language has been drawn up for translations among Russian, Czech, English and Indonesian.

Moscow linguists are pursuing their investigations of a linguistic "middleman" in another direction. They are drawing up a matrix of relationships between the elements of the languages between which texts are to be translated. This will provide a purely logical basis for translation, without the introduction of intermediate languages.

Other types of machines requiring special "languages" are information retrieval and bibliographical machines, though a "logical" language is not essential. What is needed is an abstract language of arbitrary symbols for programming the machine. Such a language will pave the way for automatic programming. Translation of a programme from the language it is written in into the built-in language of a machine will enable the machine to understand the problem fed into it and draw up the necessary programme for its solution. Such a symbolic machine language has been created and is being used.

Simultaneously scientists are working to develop a machine which could "understand" the text it is translating. So as not to go through the whole dictionary to locate every word, each word is supplied with a special symbol according to which the machine immediately determines

the part of speech and part of the sentence it belongs to. Other possible variants are thereby eliminated, and the search is purposeful. But in that case, why not provide words with "sense symbols" so that the machine would know the context in which a given word could be used? Then if it came upon the combination "working class" it would not associate the word "class" with a schoolroom.

A machine capable of "understanding" the meaning of the sentences translated by it would be able to correct errors and misprints. Later on it could be used to edit its own translations. In fact, experiments have already been made in this direction. A machine was made to translate a text. The translation was then edited and fed back for comparison with the initial production. The machine duly noted the differences, and thereafter it made similar kinds of changes itself. The process was repeated several times and the style of translation became better and better. Thus the machine was taught to handle texts by analysing the work done by an editor.

Machines, you should know, are used only to translate scientific and technical texts. Fiction is out of the question at present. The reason is that the redundancy of technical jargon is much greater than of literary language. Sometimes it is as high as 80 or 90 per cent, which means that as many as 90 out of a hundred letters may be missing, yet the meaning of a text can be restored. This facilitates machine translation, but it makes it difficult for workers of different specialities to communicate. That is why more and more workers are voicing the need of creating an international scientific language with minimum redundancy, a language of languages.

In France, a group of mathematicians working under the pseudonym of Nicholas Bourbaki is putting this idea into effect. They have substantially simplified and unified the terminology of mathematical texts, appreciably reducing their redundancy. A similar task arises regarding the formal languages widely employed in science, especially in chemical formulas, algebraic signs and mathematical symbols. It is increasingly apparent that they should all be brought together in a universal "scientific code". The redundancy of these languages is very low, and if they are unified it may well be reduced to zero.

The trend for unification has extended to electronic computers. They already have so many different languages—intermediate languages, information machine languages, programme languages to replace "mute" punchcards—that scientists are seriously considering how to join them together in a universal machine language. It would be suitable for transmitting information within cybernetic systems, between machines, and from machine to man and back. Every symbol in this language would have to count and its redundancy would be zero.

Generally speaking, there is a kind of universal symbol language. This is the language of mathematical logic. For language is not only a means of communication between people. It is also a means of formulating ideas. Of late, however, legitimate doubts have been voiced as to how good this logic actually is, and as this is the logic machines use the question of a single machine language has given rise to a much more important problem: how good is the "technology" of machine thinking?

Is Strict Logic Necessary?

The monkey hesitated for a moment, its outstretched hand hovering over the table. Then, with a grimace of impatience, it began to snatch up the pieces of cardboard, mirror fragments and balls of paper laid out on the table. Beneath each object was a small depression. All but the penultimate one were empty. In this one lay a slice of banana. The monkey grabbed the titbit and ran to a corner of its cage.

The experimenter hid another slice of banana in one of the depressions and covered them all up again. This time the monkey acted more purposefully, as if it had developed a plan of action, and naturally, it found the morsel much faster and with less effort. For now it was looking for food hidden under a piece of cardboard.

This experiment was carried out by the American neurophysiologist Karl Pribram to trace the monkey's "thought" processes. The animal's task consisted of two parts: the search for food hidden under one of several scattered objects and the choice of one object among several in a series of confrontations. In the experiments the number of objects from which the monkey had to choose was gradually increased. If the problem were solved by the method of trial and error, as a cybernetic system does, the number of trials preceding a successful outcome would be proportional to the number of objects from which the monkey had to choose. At first, when there were only five or six objects, this was in fact the case. But by the time the number of objects had increased susbtantially the monkey had gained experience. As a result the number of unsuccessful

trials grew less. The brain had developed a definite procedure corresponding to the situation with which it was confronted. Its method of search became simultaneously more active and more economical.

This was expressed by the fact that less attention was given to all the various possibilities presented by the confrontation. Having gained experience the monkey's brain could reach a decision on the basis of a few essentials. The finer details are either guessed or somehow taken for granted. The logic of the brain's operation becomes less rigid and more flexible and it learns to take account not only of the obvious, but of the less obvious as well.

Further observations revealed that different areas of the brain are responsible for various logical operations. The selection of signals arriving at the brain (in this experiment they refer to the first stage, the search for food) is apparently effected by an area located at the junction of the parietal, occipital and temporal lobes. The actual selection is carried out by the respective subcortical ganglia. The area mentioned determines the purpose of the contemplated action and isolates the main problem. The method of solving the problem (that is, the plan according to which the required object is chosen from a number of objects) is determined by another section of the brain in the forward areas of the frontal lobe.

How does the human brain deal with logical problems? We think in words. We use words and sentences to formulate and handle generalized concepts and to form judgements. From judgements we develop conclusions, which represent a higher logical construction.

Our thoughts take the form of concepts, judgements and conclusions. The formation and interrelation of these aspects of thinking are studied by the science of logic. This not very usual science dates back to Aristotle, who established the basic laws of thinking, deduced the rules according to which judgements are formed and defined prohibited procedures of reasoning.

Many of the latter are immediately obvious. You need not be an expert logician to say that a logical law has been violated in the statement, "Twice two is four, therefore zebras live in Africa." Here two incomparable things are placed in dependence.

Not all logical fallacies are so apparent. This is seen in the great number of famous paradoxes, like the one of Achilles and the tortoise which claims that the fleet-footed Achilles will never catch up with the tortoise as long as the latter is moving. The proof of logical fallacies is difficult not only because one may not know the laws of logic but also because the logical reasoning may be obscured by the wording of the statements. Scientists have long come to the conclusion that logic, like every exact science, is in need of a language of its own. This, of course, would have to be some kind of generalized language which could be used with equal success to convey the reasoning of a chemist, engineer, astronomer or biologist.

Such a language has been developed. In it every type of reasoning is denoted by an arbitrary symbol, like the symbols of mathematics. Thanks to its mathematical rigour, the new logic has proved very convenient for "intelligent" machines. "On-off" is the logic of electronic

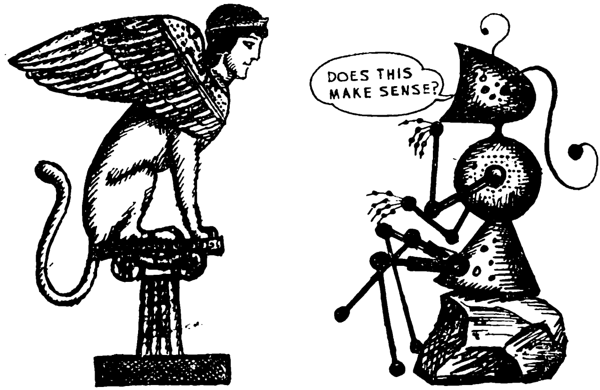
valves corresponding to "yes-no" answers or to statements like "true-false", the simplest kind of reasoning.

Machine logic is enhanced by building in the conjunctive "and" and the disjunctive "or", achieved by joining valves in parallel or in series. For an "and" signal two valves must fire together, for an "or" either one or the other must fire.

The builders of cybernetic systems are very proud of the cast-iron logic of their creations. "Their reasoning is not subject to vascillation," the engineers say. "If a machine has 'thought something out' it will be a 'cast-iron solution', not like human reasoning, when a person is often unable to say something for sure."

Yet is it really so bad that human thoughts do not follow a rigid "cast-iron" pattern? After all, the world around us and the laws we learn do not fit into an absolutely rigid pattern. The world is full of indeterminancies, contingencies and changeabilities, and the human brain can only benefit from retaining freedom of logical choice.

This point was demonstrated with special force when a machine and a person were made to perform the same kind of task: pushing buttons on a control panel. The experiment, carried out at the Institute of Higher Nervous Activity, was described by Professor Alexeyev at a conference on bionics. There were two buttons which had to be pressed to evoke a click. However, the response was not invariable and the clicks followed an unknown pattern. For example, pressing the right-hand button evoked a click every third time while pressing the left-hand button evoked clicks at random intervals. The task was to achieve as many clicks as possible within a given time. The human subject was found to be not al-



ways logical in his actions. Sometimes he would make "illogical" jumps, even when things seemed to be going well. The number of such "illogical actions" was as high as 65 in 100 pressings of the buttons, increasing towards the end of the experiment. The less the probability of a click being heard in the earphones the more rigid was the logic of selection and the less arbitrary the subject's behaviour.

The machine, on the other hand, remained strictly logical to the end, with the result that it soon fell behind the human subject. This inflexibility of behaviour explains why machines are so inherently unintelligent. They dutifully carry out all the built-in logical operations. With conscientious stupidity they scan through all possible variants in their memory stores. Modern machines are idiotically logical, scientists say. "Intelligent idiots" is the definition of electronic machines given by one physiologist.

Thanks to his "non-rigid" logic the human subject was able to establish the pattern of responses much faster than the machine. Such deviations from a strictly logical pattern of reasoning are essential to the living and thinking brain. It is in this seemingly "illogical logic" of cerebral activity that the accelerated method of step search for a correct solution displays itself.

We rarely make use of rigidly logical reasoning and resort to it either in very simple situations or at the conclusion of a task, when our creative work is over and only pure "computation" remains.

Our basic reasoning takes place outside the confines of formal logic. This is why one often finds it difficult to explain how one has arrived at some conclusion or other or solved a problem in some roundabout, nonmathematical way. For imagination, intuition and, finally, fantasy, play an important part in our thinking processes.

If we want machines to approach the brain even remotely we must supply them with human logic, with the operational laws according to which the living brain functions. This is all the more important at a time when engineers are contemplating the development of specialized logical machines. Machines not for computing, control or analogue studies but machines capable of checking the assembly of complex engineering systems such as television sets, wireless receivers or control instruments.

Such an experimental machine was used to check the circuiting of its electronic brothers. Each unit had more than 4,000 connections in it, and in several cases the machine detected up to eight faults in units which had passed through

the hands of skilled quality viewers. A machine like this must have a "cast-iron" logic. Other electronic machines, called "optimizers", have been built for determining the optimum control parameters in complex technological processes. In earlier electronic systems an analogue of the process was developed and the optimum parameters established by trial and error. This was done by a human operator whose judgement may often be subjective.

Now the work is done by an unbiased machine. There is obviously no need for it to try out all control values in search of optima. Much better results can be achieved by replacing rigid logic by a system of selection in which the machine's objectivity is coupled with human logical reasoning. Such a control system will not have to adhere blindly to a once accepted mode of operation. It will be capable of manoeuvring and even rejecting a standard solution in favour of a non-standard one. Not being a rigid automaton it will know what to do when confronted with unexpected circumstances.

Different methods of building the thinking techniques of the living brain into machines are being devised. One is to have a person at a control panel operate an electronic analogue of the process to be controlled. Step by step he varies the control parameters until no further improvement is obtained. Optimum performance has been achieved. From this record the controlling device itself is developed.

The best thing, though, would be to build a machine capable of solving problems and reasoning along the lines of the living brain. We need hardly dwell on its advantages.

Algorithms of Learning

The examination was an unusual one. The examiner was a machine, looking rather like a cash register from a department store, and it was putting questions to its builder, Lev Landa.

"I have worked as a school teacher for many years," Lev Landa relates, "and, probably like other teachers, I frequently found that a student's knowledge of, say, the theorems and rules of mathematics did not necessarily mean that he could apply them to the solution of problems. One could say that his knowledge and his ability to make use of it are stored away on different shelves in his memory and he is unable to bring them together. As a matter of fact, we teachers usually do no more than teach our pupils only the rules and formulas, leaving them to develop their thinking abilities as best they can. The more capable students develop correct thinking techniques intuitively. Less capable students frequently leave school with a body of passive knowledge and without the ability to employ it usefully."

Although he had studied the theory of education, Lev Landa was unable to say at the beginning of his teaching career how one ought to teach school children the difficult art of thinking. Logic is taught in many schools, but this apparently is not enough. Pupils may learn about correct and incorrect ways of expressing their thoughts without becoming able to think any better. They remain incapable of making use of their knowledge.

Apparently, school children must be taught to think, to reason, to formulate conclusions. As

the cybernetician would say, it is necessary to find out the algorithms of logical reasoning and teach them to the pupils. Landa split up the process of solving geometrical problems into a number of operations. When he used this method in the eighth form the results were excellent. Pupils who had studied geometry for two and a half years without having really learned how to solve problems rapidly developed an aptitude for geometry. After a short course in algorithms they could easily solve most of the problems which had formerly been quite incomprehensible to them. Landa extended his researches and proceeded to develop algorithms for language teaching. When he applied them in class the pupils improved remarkably.

Still, despite obvious successes, every now and then inveterate slackers would appear among Landa's pupils. There seemed to be no explanation, for they knew the secret of correct thinking. An indefatigable researcher, Landa decided to get down to the root of the problem. He called one such slacker to his office and said:

"Now please be quite frank and tell me why you got a poor mark again? Let us repeat the operations you were to have followed."

"There's no use repeating them," the pupil said. "I know them by heart. I just didn't feel like thinking..." This brought it home to Landa with particular clarity that an algorithm for this or that subject is not enough. What is needed is an algorithm for the teaching and learning process itself. In other words, knowledge must not simply be handed on to the pupils: the teacher must actively monitor and control the teaching and learning processes.

To the teacher a pupil is like the "black box" with which engineers like to compare the human brain. The teacher knows that he has "fed" certain information into the pupil's head. He does not know what has been understood, what has remained in the memory store and what has slipped away. All he has to go on is the result: the pupil solves problems better or writes better, or neither.

The question that arises in the latter contingency is what has failed to "click" in the pupil's brain? One can only guess, for everything going on in a child's mind during a lesson is as hidden from the teacher as the physiological processes going on inside the "black box" of the skull. Yet scientists have learned to control many physiological processes. Why not try to control psychological processes in education? This, of course, is much more difficult, but in principle it should not be impossible. The human brain, to be sure, is a "self-programming" device, but this doesn't mean that it should be left on its own. The thing is to participate in the brain's self-learning processes and guide its psychological growth and development.

Good control requires good feedback, and this is what modern teaching processes lack. The teacher may explain a lesson in the finest detail, yet the pupil may be daydreaming and thinking of other things. Or, like Landa's pupil, he may be too lazy. In either case the teacher's efforts will have been in vain. An effective system of instantaneous feedback would make all the difference in the world.

Is this possible? It has been estimated that in the course of a twenty-five minute lesson a teacher

must receive at least one hundred and fifty confirmations that one pupil is listening and understanding his explanations, and a class consists of twenty or thirty pupils. From here it was one step to the idea of entrusting the control functions to an electronic machine. Let information from each pupil be fed into it and let it determine the quality of their knowledge and give them new assignments.

Imagine a class in which the pupils do not have to answer aloud. Each one has a panel before him. When a problem is flashed on the screen the student presses a "response" button on his panel. If he is slow because of ignorance or inattention a "response monitor" gives him a "minus". Such a teaching device would keep the pupil's attention concentrated on his task; it would take account of individual abilities and enable each pupil to work at the rate best suited to him. Most important, by participating in the learning process and signalling a mistake at the time it is made, it would prevent incorrect habits and erroneous logical constructions from being formed.

In a sense such machines are "diagnosing" systems. Only instead of diseases they disclose "disorders" in thinking processes. After memorizing all of a pupil's fallacious logical actions it gives the teacher a detailed diagnosis of his thinking processes.

One such compact electronic system could control the teaching and learning processes of a whole class, giving a corresponding improvement in teaching efficiency. Such machines are still in the experimental stage, but simpler modifications in the form of examination and coaching machines are already on the way in.

Lev Landa's teaching machine can be used to teach grammar. A sentence is written down for the pupil and punched on a card for the machine. The machine compares the sentence with the data in its store and analyses it. The pupil feeds his answers into the machine by pressing buttons on the console. The machine flashes on a green light for correct answers and a red light for wrong answers. It summarizes all the answers and prints out the pupil's mark.

At the Moscow Power Institute there is a machine examiner in cybernetics! One hundred questions on automatic control theory were written down, coded and fed into it. The student has to press a button and a question, chosen at random by the machine, flashes on a screen. The questions are so designed as to practically exclude the possibility of giving a correct answer by pushing the "response" buttons at random. The machine's programme takes account of the difficulty of each question and the time needed to think it over. The correct and wrong answers are recorded. If the "wrong answer" counter fills too rapidly, the machine stops and gives the student a poor mark.

There are other types of teaching machines. In the United States, for example, an examination machine confronts the student with a selection of four or five answers to a question. The student must choose the correct one. It is still early to say what teaching machines will evolve into, but there can be no doubt of their usefulness. In fact, educational authorities in the Soviet Union and other countries have given them the green light.

Teaching as such is not the sole aim in developing such machines. The idea is to apply the ideas

and methods of the science of control to improve the teaching process. Essentially this means improving thinking techniques and developing a more workable and effective logic. Teachers, engineers and scientists all agree that it is high time to rennovate the science of logic.

Educators are viewing the growing burden imposed by modern knowledge on students with great concern. The question of how the mind is to cope with the whole body of science is an urgent one. Obviously, besides such administrative methods as revising school curricula and syllabuses it is necessary to improve the teaching and learning process so that students would be able to digest a maximum of information in a minimum of time. This calls for an improvement in thinking techniques.

Another aspect to be considered is that of "packaging" knowledge in a way which would enable the student to master as much as possible. This, too, will require the development of a new logic to formulate the laws according to which knowledge is generalized and summarized.

This is not only a question of mastering what is already known. Of equal, if not greater, importance is the acquisition of new knowledge, which also cannot be carried out successfully with the old ways of thinking. As the British scientist George Thomson wrote in his book, *The Foreseeable Future*, "Just as the early seventeenth century gave man the beginning of physical science by Galileo, Kepler and Gilbert, so our age marks the beginning of knowledge about thought."

We thus find that progress is impossible without the improvement of thinking processes. But this, in turn, means that "thinking" machines

will never be able to catch up with man after all. While they are mastering the old human techniques of thinking, the creative thought of man will forge far ahead.

From a Machine's Point of View

There can be no doubt that the idea of "intelligent", "thinking" machines has captured the imagination of many people all over the world. In Moscow, bigger crowds flocked to lectures by Alexander Kolmogorov, Norbert Wiener and other prophets of cybernetics than to the performances of famous prima ballerinas. People want to hear more about cybernetic systems, they want to know what new fields of human activity have been relegated to automatons. Inevitably the question arises: how far can all this go? Will the time really come when machines will be able to "think" like human beings?

The progress in cybernetics can be traced according to the questions asked by the layman. There was a time when the very combination of words, "thinking machine", smacked of heresy. But gradually machines learned to perform a great many tasks. Computers developed into industrial regulators and controllers. There appeared electronic train dispatchers and bookkeepers, bakers, steel-makers and chemists. These were followed by translating, abstracting, reading and speaking machines. Someone even built a machine capable of writing music and verse. As a result the lay and scientific public fell into another extreme and people imagined that machines could be adapted to all spheres of human activity without exception.

In Norbert Wiener's opinion the danger exists that learning machines will begin to live lives of their own and that as we come increasingly to rely on their "thoughts" and "decisions" they will commit us to courses of action which may destroy us. Wiener cites the moral that is to be found in W. W. Jacobs' famous horror story of the monkey's paw. The wizened object is endowed with the power of granting three wishes, but it brings nothing but disaster to those who use it. Although warned against it, its possessor wishes for 200 pounds. Soon there is a knock at the door and the possessor of the paw is given this sum as compensation for the death of his son, who has just been killed in a factory accident. Grief-stricken, the father uses his second wish to get his son back. A horrifying apparition—evidently the son's ghost—promptly appears. The father's last wish is to have the ghost return to the dead.

I think that Wiener took a too pessimistic view of the future of cybernetics and that we shall not "find the ghost knocking at our door".

As cybernetics has progressed the various issues associated with it have become clearer. The great abilities of machines have been explained scientifically and the very nature of the question has changed. Today people discuss the limits of machines' abilities in a completely matter-off-fact way.

Here, too, opinions naturally vary. Some cyberneticians think that the time may come when machines will become "cleverer" than their makers.

According to one line of reasoning, a genius is a man who is more capable of extracting the essential from a mass of nonessentials than the average man. Computers can carry out such a

selection much faster than a human being. Therefore a talented designer may create a machine that would be more talented than he is himself. But the fact that machines are capable of replacing or even surpassing man in some spheres of activity does not mean by far that they can replace him in general, even though they can count a hundred thousand times faster than he can.

It is suggested that a machine can be rated as "thinking" if it can replace a person in a quiz game and that such a machine could be said to possess consciousness.

Thus the question, "Can a machine think," has turned into the question, "Can a machine have consciousness?" The distance from "thinking" to "consciousness" is great. Some animals display rudiments of thinking but no animal is capable of conscious action, which requires the development of a definite attitude towards things and events and not just passive awareness of the environment.

It is in this broad context that the difficult problem of "thinking" machines must be considered. If a machine can have an opinion about a question, then it thinks independently. If it lacks this "ego", it will remain a thoughtless, or rather feelingless, automaton. When we raise the question of a machine's "consciousness" we are already on the psychological plane, which is, broadly speaking what Alexander Kolmogorov discusses in a number of papers. He has posed the problem in no equivocal terms: shall we ever create an artificial creature endowed with psychological qualities?

Let us see whether this is possible. First of all, what is meant by psychological qualities? Placed in a nutshell, these cover all human emotions

and moods. They do not develop spontaneously but appear in response to events and phenomena around us. Our psyche is a sort of tool for sensing the surrounding world. Cognition of any phenomenon passes essentially through two stages. First we perceive the environment through our sense organs. Information concerning optical, auditory and other stimuli reaches the brain. It is processed and the initial impressions of objects—sense impressions of individual properties—appear in the brain.

A sense impression is the result of the perception of a set of nerve impulses by the brain; this is the first stage of psychological activity.

The brain combines individual sense impressions into a composite image of the object which appears in the brain at the moment the object acts upon the sense organs.

Gradually the brain learns to reproduce images of objects and phenomena mentally, even when they are not before one's eyes. Cybernetic systems do nothing even remotely approaching this kind of activity. No machine has anything like sense perceptions. They are barely capable of modelling the physiological processes that take place in the visual, auditory or other areas of the cortex when they are stimulated by nerve impulses coming in from the eyes, ears and other sense organs. The psychological aspects (which are not at all clear, incidentally, to the scientists themselves) are quite beyond the abilities of the best machine.

Our sense impressions are logically processed in the brain to give us a deeper understanding of the things going on about us. This is the second, the logical stage of cognition, thought as such, so to say.

As a result, internal qualities of things and events are opened up to us, qualities which cannot be perceived by merely inspecting or fingering them. (Compare our knowledge of an apple and the atomic nucleus.) It is thanks to this that we become aware of the laws governing various phenomena and develop generalized, abstract notions of the outside world.

You know that language, its words and sentences, are the means by which we formulate our thoughts. In this respect "speaking", "hearing", "reading" and "writing" machines of all kinds come no closer to the thinking brain than their cousins, the conventional digital computers. Cybernetic systems lack the faculty of speech. They can do no more than reproduce the superficial manifestations of speech: articulate sounds, or, in the case of a writing machine, draw letters.

What about reading machines? you may ask. They do not read like the brain does. You remember that not knowing how reading occurs in the brain the scientists found a way out by making a machine learn to read from experience. What they in effect reproduced was not the process of identifying letters but the development of habits by repetition. That is, they copied one of the mechanisms of learning. All other learning machines modelled on conditioned reflex mechanisms reproduce only the simplest actions of the higher nervous system. Because they are well developed both in man and in animals these machines have been dubbed "vertebrate" systems.

There are machines capable of operating according to a flexible logical scheme. They represent the first breakthrough in the wall separating machine and human behaviour. There can be

no doubt that in future more and more such breakthroughs will occur. But this means nothing more than that we shall get to understand yet other aspects of thinking techniques, that we shall unravel yet other mysteries in the mechanism of intelligence. And whatever we comprehend can be described in terms of specific schemes and rules which can be reproduced by a machine.

One might gain the impression that if the brain is so much better than the best machine there is no use of designing clumsy mechanical analogues of it. But we should remember that despite its high degree of perfection the brain is a relatively slow worker. An ordinary electronic tube can perform the same kind of operation as a brain cell a hundred thousand times faster. Furthermore, the nervous system is a machine which performs its extremely complex work with a fairly low degree of accuracy. Our brain tires and its attention is frequently distracted. This is why "extensions" of the brain without such shortcomings are so useful. They work with absolute accuracy and lightning speed and they never tire. In this sense electronic machines fall into the class of tools which man has been inventing since time immemorial to improve on his own meagre facilities. They are an extension of the brain just as the microscope and telescope are extensions of the eyes and the automobile is an extension of the feet. Cybernetic systems already surpass the brain in many ways. They are capable of storing stupendous quantities of information. A bibliographical machine can be regarded as an extension of the human memory.

Computers tremendously enhance the brain's ability to calculate. They solve in two hours the ponderous system of equations predicting tomor-

row's weather, a job it would take five weather men a fortnight to do. High-speed computers capable of making two million additions a second have been built, and machines with double this capacity are quite feasible.

Finally, controlling, translating, game-playing and other "intelligent" machines capable of choosing the best out of a number of variants or of selecting words and sounds according to programmed rules enhance the logical capabilities of the brain.

We see that electronic machines improve upon different aspects of mental activity. The future of logical machines is undoubtedly fantastic, especially when we consider that they can already "learn", "take examinations" and develop their "creative" abilities. In time they will perform more and more complex logical operations. It has been suggested that machines will replace the engineers responsible for "teaching" other machines. Such a machine could, for instance, press a button to switch on a bell or a light at the required moment to produce a conditioned reflex in its electronic neighbour. Machines will invade various spheres of mental activity. They may start with carrying out certain functions of scientific thinking, which must follow the laws of logic as closely as possible. They will probably also be used to carry out the less formal stages of thinking. For example, they may cope with the processes immediately preceding the final logical formulation of an idea, that is to say, the earlier stages of creative search.

It is hardly possible or necessary to attempt to define the limits of applications of cybernetic systems. The important thing is that as soon as we get to know the specific mechanisms under-

lying creative work we shall be able to make machines perform it. As soon as we get to know what imagination consists of we shall be able to build this process into a machine.

The inevitable question then is: suppose we continue to improve on machines until one fine day they become as good as the human brain and start thinking up things for themselves.

Incidentally, they will not have to be like the bulky electronic machines of today. Tiny semiconductor elements are already replacing electronic tubes. There are projects for "growing" machine elements out of solutions in the same way as crystals are grown. Recent reports speak of new wonderful devices with physical properties analogous to the nerve cell. In them ions circulate instead of electrons, the same as in living matter.

Perhaps in time cybernetic systems will be stuffed with living cells made artificially out of inorganic matter. If these cells are arranged in the by that time known scheme of the brain and made to work—does this mean that we will have built a manmade apparatus duplicating all the features of the human brain? Yes, but this will no longer be a mechanical device. It will be a manmade brain.

But why follow blindly in the footsteps of nature? Better neuron circuits that exist in the human body are already being discussed. These may eventually give rise to improved variants of the brain. For although nature has not done a bad job in creating you and me, it would be ridiculous to declare that nothing could be better.

As for technical replicas of the brain, however like the living brain they may be, they will never be able to think for themselves. In fact, there

is much more in common between the brain of man and ape than between the brain and an electronic machine.

Machines will forever remain "learned idiots" because they will never be able to think or perceive for themselves, they will never have a point of view of their own. For this a machine would have to be a creature living in society and engendered by society. A human being isolated from society ceases to be a thinking creature. This was the fate of Maugli and other fictitious or real children reared by animals.

"No machine is capable of posing problems that have not been posed to it by its designer," says Dr. E. Kolman, director of the Czechoslovak Institute of Philosophy, as he discusses cybernetics with Alexander Kolmogorov. "For machines which are capable of developing work programmes for themselves can do so only insofar as self-programming has been programmed for them."

Cybernetics, we find, does not clash with the materialistic foundations of dialectics. On the contrary, the achievements of manmade machines capable of performing different kinds of mental work strike at the very root of the idea that man has received his remarkable abilities out of the hands of God.

INDEX

To the Reader

Peace Publishers would be glad to have your opinion on the translation and the design of this book.

Please send all your suggestions to 2, Perry Rizhsky Pereulok, Moscow, U.S.S.R.

Printed in the Union of Soviet
Socialist Republics

2-E

ABOUT THE BOOK

Can a rat tell the difference between a Raphael Madonna and a Picasso Girl in Blue? Would a Martian (if there is such a thing) recognize a live cat after having seen a photograph of one? Can a "seeing"electronic machine be made to tell a cat from a dog or an A from a B? How would it go about "computing" the image? And is "machine thinking"anything like human thinking?

These and other such problems are investigated in the branch of cybernetics that studies living systems: bionics, as this ultramodern science is now called. It developed when scientists began to compare the design and operation of electronic systems with living organisms. Our body, they found, is a complex cybernetic system controlled by countless self-regulating devices. In fact, every single cell of our body is an automatic control device in its own right. Millions upon millions of tiny cybernetic units are constantly at work within us. They maintain normal blood pressure, control the composition of the gastric juices, ensure the rhythmic contraction of the heart and lungs, and do a thousand other things that come under the heading of "vital functions"of the organism.

How they work and how our body functions is described in this popular exposition, which requires no previous knowledge of cybernetics, biology, electronics, or any other subject for that matter (except reading, of course).

MIR PUBLISHERS MOSCOW